TREATABILITY STUDY FOR HILL AFB'S OPERABLE UNIT-1: ENHANCED MICROAEROBIC DECHLORINATION USING VARIOUS ELECTRON DONORS

by

Peter G. Breed

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Approved:

Michael J. McFarland, Major Professor

Darwin L. Sorensen, Committee Member

Daniel Stone, Committee Member

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ABSTRACT

A treatability study of the microaerobic biodegradation of *cis*-dichloroethene (c-DCE) was completed using a series of eight continuously operated columns filled with contaminated soils from Hill Air Force Base's Operable Unit 1. Columns were supplied groundwater from the site, vitamins and yeast, and an electron donor solution containing one of the following donors: n-butyric acid, benzoic acid, lactic acid, propionic acid, n-propanol, or toluene. Concentrations of c-DCE varied over six months and ranged from 2736 µg/L to 30 µg/L. Though attempted as an anaerobic study, the ability to continuously eliminate oxygen from an active system proved difficult and columns operated as microaerobic systems.

In all columns the degradation of c-DCE was observed, however, the removal efficiencies determined by comparing the influent and effluent concentrations were highly inconsistent throughout the experiment. By comparing the background columns to the columns supplied electron donors, it does not appear the addition of vitamins or electron donors enhance the indigenous microorganism's ability to remove c-DCE. While c-DCE removal within the background column averaged 17%, the vitamin amended control column averaged only 7% c-DCE removal within the column and the electron donor supplied columns averaged between 7% removal and 5% apparent production. Of the electron donors supporting c-DCE removal, benzoic acid demonstrated 7% removal followed closely by propionic acid and n-propanol, both showing 5% c-DCE removal.

The accumulation of vinyl chloride (VC) was initially noted in all columns, but rapidly declined until typical operating conditions showed persistent and complete removal of VC. Ethene removal appeared in all columns and was typically an order of magnitude greater in columns provided with an electron donor. Methanogenesis was apparent in all columns with methane production in the vitamin and electron donor columns being two to five times greater that the unamended control column.

This research identified the critical need to determine in situ limitations before enhanced bioremediation is attempted. The lower threshold concentration of the contaminant of concern and the acclimation period for indigenous microorganisms must be adequately defined before remediation predictions or field applications can be accomplished.

CHAPTER I

INTRODUCTION

The contamination of soils and groundwater by waste solvents such as the chlorinated ethenes tetrachloroethene, trichloroethene, dichloroethene, and vinyl chloride (PCE, TCE, DCE, and VC respectively) is of significant environmental concern. These chlorinated aliphatic hydrocarbons (CAHs) have been widely used as solvents in many industries including the aerospace industry. Their subsequent release and disposal has commonly resulted in contamination of the groundwater and soil. Due to the toxicity of these compounds and their known or potential carcinogenic affects, the U.S. Environmental Protection Agency has listed many of them as priority pollutants (40CFR 141). As a result of the persistence and toxicity of some CAHs, natural attenuation, which occurs at some sites, may not be adequate to protect human health and the environment. At many contaminated sites, some form of active or enhanced remediation should be considered as a more rapid option for site clean up.

The area known as Operable Unit 1 (OU-1) located on Hill Air Force Base, Utah, contains significant levels of CAHs and is characterized by high levels of PCE and TCE daughter compounds, particularly the *cis* isomer of DCE (c-DCE). Past site investigations completed by the Air Force show worst-case groundwater contaminant levels of PCE at 58 micrograms per liter (μg/L), TCE at 2,300 μg/L, total DCE dominated by the *cis* isomer but including the *trans* isomer (t-DCE) at 42,000 μg/L and VC at 2,400 μg/L (Montgomery Watson, 1995). These levels represent source area concentrations and are much higher than average concentrations encountered in OU-1 groundwater. Any clean-up strategy for OU-1 groundwater will be dominated by the treatment of DCE and VC with very little PCE and TCE present. The average concentration of c-DCE to be treated would likely be 1,000 μg/L or less. As a result of known or suspected health affects from these compounds, the EPA has established drinking water Maximum Contaminant Levels (MCLs) for each of them. These MCLs and some other physical and chemical properties of concern are listed in Table 1.1.

Reductive dehalogenation of CAHs has become widely recognized as a technology with great potential for in situ remediation. Current work by the Department of Defense shows that Reductive Anaerobic Biological In Situ Treatment Technology (RABITT) is one of the

most promising in situ treatment technologies for chloroethenes (Morse *et al.* 1997). The more highly chlorinated ethenes PCE and TCE resist aerobic degradation while the lesser-chlorinated compounds of DCE and VC are readily degraded by a variety of aerobic microorganisms. It has been demonstrated, however, that all chloroethenes can be degraded under anaerobic conditions (Freedman and Gossett 1989, DiStefano *et al.* 1991 and 1992, deBruin *et al.* 1992, Carter and Jewell 1992, Beeman *et al.* 1994, Fennell and Gossett 1997, Smatlak 1996, and Yager 1997). Research has discovered that if the proper electron donor is available, anaerobic or microaerobic microbes, possibly indigenous to a contamination site, can completely dechlorinate these compounds into innocuous byproducts. However, if the site does not have an adequate microbial population or an adequate source of electron donors, PCE and TCE may persist or reductive dechlorination may proceed only as far as the intermediate daughter products, specifically the DCEs and VC. For remediation to be considered complete, these intermediates must also be dechlorinated to ethene (ETH) or ethane.

Table 1.1. Chloroethene Properties and MCLs

Contaminant	MW[(a)] (g/mole)	Vapor Pressure (mm Hg) @25°C	Density (g/mL)	Solubility (mg/L) @25°C	OU-1[(b)]Maximum Concentration (µg/L)	MCL[(c)] (µg/L)
PCE	165.82	19	1.623	150	52	5.0
TCE	131.38	77	1.465	1100	2300	5.0
1,1-DCE	96.94	591	1.213	2250	N/D	7.0
cis-DCE*	96.94	206	1.282	3500	42000 (Total)	70.0
trans-DCE*	96.94	331	1.255	6300	9.3 Estimated	100.0
VC	62.50	760(STP)	0.911	2700	2400 µg/L	2.0
Ethene	28.05	760(STP)	1.260	131		-

(a) Perry's Chemical Engineer's Handbook, 7th Edition
(b) Montgomery-Watson, 1995
(c) EPA Drinking Water Regulations and Health Advisories, October 1996
* The cis and trans isomers of 1,2 DCE can be analytically distinguished, however, sample results show only trace levels of trans therefore, they are discussed as a portion of the Total DCE

The goal of this research project was to show that enhanced anaerobic or microaerobic bioremediation, facilitated by electron donor addition, is a viable alternative to the pump and treat methods currently being proposed for Hill AFB's OU-1 groundwater contamination. This project successfully demonstrated partial removal of the primary contaminant, c-DCE,

without the accumulation of VC, however the best removal efficiencies were in the background column that was not provided an electron donor. Though this experiment did not clearly demonstrate that electron-donor-enhanced in situ bioremediation is a more cost-effective alternative than the proposed pump and treat methods, further research should be completed before this technology is disregarded.

CHAPTER II

RESEARCH OBJECTIVES

The overall objective of this study was to determine if in-situ enhanced reductive dechlorination is a viable alternative to pump-and-treat technologies currently proposed for the remediation of Operable Unit 1. The focus of this research was on stimulating indigenous microorganisms to reductively dechlorinate the relatively high levels of dichloroethene contamination. Stimulation of these organisms was attempted by supplying nutrients and additional substrate in the form of electron donors. To be completely successful, enhanced reductive dechlorination had to lower the level of all chlorinated ethenes to below regulatory standards. The specific research objectives were to:

1. Demonstrate that complete reductive dechlorination of *cis*-dichloroethene without an accumulation of vinyl chloride is possible under anaerobic or microaerobic conditions using OU-1 soil and groundwater.
2. Compare the suitability of various electron donors and determine the most promising electron donor(s) for maintaining reductive dechlorination under OU-1 site conditions.
3. Determine if vitamin and yeast amendments are necessary for complete reductive dechlorination in OU-1.
4. Demonstrate a cost-effective alternative for remediation of chlorinated ethenes at OU-1.

CHAPTER III

TREATMENT STUDIES

Past studies have demonstrated that chlorinated solvents can be reductively dechlorinated to ethene and ethane under anaerobic conditions. Successfully accomplishing complete reduction to these innocuous compounds is dependent on at least two key parameters: an adequate microbial population capable of completing this reduction and a sufficient supply of electron donors. Various researchers have focused on these two key variables and have successfully identified microorganisms and electron donors that support reductive dechlorination. (See Tables 3.2-3.4).

The reductive dechlorination model shown in Figure 3.1 is accepted as the general anaerobic transformation pattern for chloroethenes. In the previous studies reviewed, either a portion of the reductive dechlorination sequence model (e.g. TCE → DCE) or the complete

Figure 3.1. Reductive Dechlorination Model

transformation model (e.g. PCE → ETH) is demonstrated. Most studies and typical field sites demonstrate that PCE and TCE are the initial sources of contamination while DCE and VC are shown to be daughter products of their reduction. In general DCE, dominated by the *cis* isomer, is the most persistent daughter product found at field sites. This may be the result of the much slower kinetics for the DCE → VC step than the TCE → DCE step, but may also be due to the exhaustion of available electron donor supply. Historically, microcosm studies examined c-DCE reduction as an intermediate step in the complete reduction of PCE or TCE to ETH. More recently, studies began to target c-DCE reduction specifically and the observations support this project and suggest a great potential for stimulating c-DCE reduction by supplying adequate electron donor supplements (Yang and McCarty, 1998 and Windfuhr 1998).

CHLOROETHENE REDUCTION

Organic compounds have been biotransformed through three identified processes: (1) as an electron donor in energy metabolism, (2) cometabolism, and (3) as an electron acceptor in

energy metabolism (Adriaens and Vogel, 1995, Wackett 1995, and McCarty 1998). Under anaerobic conditions, reductive dehalogenation is the dominant mechanism for halogen removal (Mohn and Tiedji, 1992) and until recently, it was believed that all dechlorination of chloroethenes was a cometabolic process occurring as a beneficial result of other dominant electron receptor reactions. In these fortuitous reactions, the chloroethene is reduced, but the microorganisms receive no energy from the reaction. Recently, research has elucidated the microbial process called halorespiration (Hollinger and Schumacher, 1994) in which chloroethenes are used as respiratory electron acceptors and support metabolism which provides organisms with energy for growth and maintenance. As metabolism proceeds, electrons are transferred from donors to the chloroethenes in a manner that substitutes a hydrogen atom for a chlorine atom. In short, if energy is obtained directly from the dechlorination the process it is called halorespiration and if no energy is obtained it is reductive dehalogenation (McCarty, 1998). Synthesis of new cells from the carbon available in chloroethenes apparently does not occur in either cometabolism or halorespiration reactions. The carbon source for synthesis is not well understood.

The reduction half reactions defined in Table 3.1 show the relative energetic favorability of common environmental electron acceptors and chloroethenes. The Gibb's free energy

Table 3.1. Electron Acceptor Reduction Half Reactions

Half Reaction	ΔG^o (kJ/e equiv)
Oxygen $0.25\ O_2 + H^+ + e^- = 0.5\ H_2O$	-78.14
Nitrate $0.2\ NO_3^- + 1.2\ H^+ + e^- = 0.1\ N_2 + 0.6\ H_2O$	-71.67
PCE $0.5\ CCl_2CCl_2 + 0.5\ H^+ + e^- = 0.5\ CHClCCl_2 + 0.5\ Cl^-$	-53.31
TCE $0.5\ CHClCCl_2 + 0.5\ H^+ + e^- = 0.5\ CHClCHCl + 0.5\ Cl^-$	-52.11
DCE $0.5\ CHClCHCl + 0.5\ H^+ + e^- = 0.5\ CH_2CHCl + 0.5\ Cl^-$	-42.12
VC $0.5\ CH_2CHCl + 0.5\ H^+ + e^- = 0.5\ CH_2CH_2 + 0.5\ Cl^-$	-45.22
Sulfate $0.125\ SO_4^{2-} + 1.188\ H^+ + e^- = 0.063\ H_2S + 0.063\ HS^- + 0.5\ H_2O$	21.27
Methane Fermentation $0.125\ CO_2 + H^+ + e^- = 0.125\ CH_4 + 0.25\ H_2O$	24.11

(ΔG^{o}) values in Table 3.1 show that oxygen and nitrate reductions are more energetically favorable than chloroethene reduction. The table also shows chloroethene reduction is more favorable than sulfate reduction or methane fermentation and that VC reduction to ETH is energetically more favorable than c-DCE reduction to VC. Therefore, based on energetics we would expect c-DCE to be the rate limiting step in anaerobic reductive dechlorination and dechlorination would be expected to be inhibited where oxygen or nitrate are in abundance or possibly where sulfate concentrations are high.

DECHLORINATING MICROORGANISMS

Since 1981, we have known that the potential for the biological transformation of chlorinated aliphatic hydrocarbons (CAHs) is possible under anaerobic conditions (Bouwer et al. 1981). Since that time a great deal of work has been completed to isolate microorganisms capable of degrading these CAHs. Though it has often been found that a consortium of microorganisms is required for complete dehalogenation, in some cases specific microorganisms have been identified.

Microcosm studies have shown that organisms frequently found in natural soils have the ability to dechlorinate solvents. In 1987, Fatherpure *et al.* completed a study comparing nine pure cultures of anaerobes and identified *Methanosarcina* sp., *Methanosarcina mazei*, and dechlorinating bacterium DCB-1 as significant dechlorinators. In batch studies, these organisms reduced 1 mg/L of PCE to TCE within one week. The DCB-1 demonstrated the highest rate of reduction and was approximately three times faster than *Methanosarcina* sp. and five times faster than *Methanosarcina mazei*. A subsequent study (Fatherpure and Boyd, 1988) showed that *Methanosarcina* sp. strain DCM could also reduce 1-3 mg/L of PCE to TCE within one week under methanogenic conditions. A direct relationship between microbial concentration and the transformation of PCE was identified. In this test some samples were autoclaved to demonstrate the critical nature of microbial activity in the reduction of the contaminant. No dechlorination occurred in the autoclaved microcosms. Also demonstrated in this study was the dependence of microorganisms on an adequate supply of electron donors.

Hollinger *et al.* (1993) demonstrated the reductive capacity of an anaerobic bacterium by reducing 200 μM (3.32mg/L) of PCE using an organism called PER-K23. PER-K23

completely reduced the PCE within 33 days. Of particular interest was the production of ethene, previously thought to require aerobic conditions. Also of interest was the PER-K23's dependence on PCE without which the bacterium ceased to grow. This marks the first documented case of microorganisms using PCE as electron acceptors in energy metabolism i.e., halorespiration.

In 1996 Gossett and Zinder presented a list of direct dechlorinators capable of dechlorinating PCE and TCE to c-DCE. This list included *Dehalobacter restrictus, Dehalospirillium multivorans*, Strain TT4B, *Enterobacter agglomerans*, and *Desulfobacterium* sp strain PCE1 (Hollinger 1992, Neumann *et al.,* 1994, Krumholz 1995, Sharma and McCarty 1996 and Gerritse *et al.*, 1996). Expanding the menu of microbial direct dechlorinators, Sharma and McCarty (1996) demonstrated the ability of a facultative aerobic bacterium, *Enterobacteriaceae* strain MS-1, to transform 1mM (165 mg/L) of PCE to c-DCE in less than 12 days. Due to the nature of this organism, the energetically preferred oxygen was depleted before the PCE was used as an electron acceptor and for energy metabolism. Column studies containing this organism and PCE contaminated aquifer soils showed complete reduction to ethene when benzoate and sulfate were added. The MS-1 did not use the sulfate and benzoate directly, but used the benzoate oxidation products, acetate and formate, for PCE dehalogenation. Later work with this microorganism demonstrated that it could be successfully used for bioaugmentation in a fixed film reactor and successfully dechlorinate PCE and TCE to ethene (Newberg *et al.*, 1997).

Reported in 1997, an eubacterium had been isolated from an enrichment culture and shown to be capable of completely dechlorinating PCE to ethene (Maymo-Gatell *et al.*, 1997). This microorganism, *Dehalococcus ethenogenes*, strain 195, was capable of sustaining dechlorination while using hydrogen as the sole electron donor. Methanol, ethanol, pyruvate, glucose, formate, acetate, lactate and yeast extract were also tested as electron donors, but none were utilized by the microorganism. PCE, TCE, c-DCE, 1,1-DCE, 1,2-DCA and 1,2-dibromomethane (DBM) were all shown to support growth of the microorganism while t-DCE and VC did not support growth but were also converted to ethene. This work is remarkable in that it identifies an isolated organism capable of completely dechlorinating PCE to ethene and it demonstrates that in many steps of the process the CAHs serve as the electron acceptors and support microbial growth. Though we

have made progress in identifying specific dechlorinators, the complete destruction of CAHs under microaerobic or anaerobic in-situ conditions likely still requires a consortia of microorganisms working together (McCarty, 1998).

Table 3.2 Past Research Identifying Anaerobic Dechlorinating Microorganisms.

Test	Dechlorination Range	Organism; Metabolic Group (Conditions)	Conclusions	Reference
Test Method not specified but assumed to be 50 mL of medium in 160 mL bottles	1 mg/L PCE for each different test	-DCB-1; Methanogen (0.2% Pyruvate, 1mM 3-Chloro-benzoate) -*Methanosarcina* sp. or -*Methanosarcina mazei*; Methanogen (25mM Methanol, PREM)	Dechlorination for DCB-1 was 3-5 times faster than the others; Complete reduction to TCE in 1 week	Fatherpure *et al.*, 1987
Microcosms: 50 mL of medium in 160 mL bottles	1-3 mg/L PCE	*Methanosarcina* sp. Strain DCM; Methanogen (25mM Methanol, PREM, 50mM Sodium Acetate)	PCE to TCE/CH4 in 1 week; Controls showed no reduction	Fatherpure and Boyd, 1988
Microcosms: 200 mL of medium in 500 mL bottles	Up to 200 μM of PCE	PER-K23; Unknown (H_2 or formate in Rhine River Sediment with anaerobic sludge, yeast extract, vitamin solution)	Degradation products including ETH in 33 days; No growth in the absence of PCE	Hollinger *et al.*, 1993
Test Method not specified	1 mM PCE	*Enterobacteriaceae* Strain MS-1; Facultative Aerobe (glucose, lactate, pyruvate, yeast, formate, amino acid or acetate in basal and vitamin solutions)	Dechlorination of PCE to c-DCE in 4-12 days at room temp	Sharma and McCarty, 1996
12-L anaerobic fixed film reactor	PCE unspecified 1-2 mg/L TCE	*Enterobacteriaceae* Strain MS-1; Facultative Aerobe (yeast extract and sodium benzoate)	Dechlorination of >95% TCE to c-DCE in 5 days	Newberg *et al.*, 1997
Test Method not specified	Not Specified	*Dehalococcus ethenogenes* strain 195 Eubacterium (hydrogen, acetate, B12, anaerobic supernatant)	Dechlorination of PCE and all intermediates to Ethene	Maymo-Gatell, *et al.*, 1997

These studies demonstrate the critical role microorganisms play in the reduction of chloroethenes. They also show that under anaerobic conditions, all species of chloroethenes can ultimately be reduced to ethene and subsequently ethane. The results of these studies support the potential use of anaerobic, in situ reductive dechlorination at CAH contaminated sites, but they also demonstrate the demand for an adequate supply of electron donors and perhaps other nutrients if the microbial population is to effectively dechlorinate the contaminants.

ELECTRON DONOR STUDIES

Site characteristics and indigenous microbial populations vary from site to site; therefore, the identification of an appropriate electron donor and needed nutrients is critical for successful in situ reductive dechlorination. A substantial amount of research has been conducted to define the effectiveness of various electron donors. It has been understood for some time that dechlorination of PCE to TCE proceeds under strictly anaerobic conditions while the dechlorination of TCE to DCE will proceed under anaerobic conditions or aerobic conditions. A review of anaerobic studies demonstrating the degradation of PCE to DCE was completed to provide some insight to what has occurred historically at Hill AFB OU-1. A brief summary of some of these studies is presented in Table 3.3. More recently, research has shown that the continued dechlorination of DCE to VC and ethene can also progress under anaerobic conditions and is not limited to the energetically favorable aerobic conditions as once believed (McCarty, 1998). Table 3.4 focuses on some of these studies and shows complete anaerobic dechlorination in a variety of experiments. Results of these studies support the theory of successful enhanced in-situ bioremediation if an appropriate donor is identified and provided.

Reduction of Tetrachloroethene to Dichloroethene

Sealed microcosm studies have been the principal method of research used to identify electron donors that facilitate dechlorination. In a comparative study of eight electron donors (Gibson & Sewell, 1992), microcosms were prepared using 10 grams of contaminated soils from a Coast Guard Station and inoculated with 30 μM of PCE. Lactate and ethanol supported production of TCE within six days and DCE after ten days. Butyrate, crotonate,

and propionate had lag times of ten to fifteen days but also showed production of TCE and DCE. Acetate, methanol, and isopropanol did not support dechlorination at a rate any higher than the unamended controls. These observations indicate there can be significant differences in dechlorination results depending on the electron donor selected.

Table 3.3. Studies Demonstrating Reduction of PCE to DCE.

Test	Source Concentrations	Successful Donors	Conclusions	Reference
Microcosms: 10 g sediment in 20 mL bottles, headspace filled with amended solutions	Soil from USCG site with 30 μM PCE	Lactate, Propionate, Crotonate, Butyrate, Ethanol	PCE reduction started within 1 week under methanogenic conditions	Gibson and Sewell, 1992
Microcosms: 50 mL of reactor biomass culture in 100 mL bottles	2.8 mM PCE	Benzoate with protein from biofilm reactor	Conversion to c-DCE completed w/o methanogenesis	Scholz-Muramatsu, *et al*, 1989
Microcosms: 100 mL of digester medium in 160 mL bottles	600 μg/L PCE in anaerobic digester sludge	Lactate with vitamin solution	92% PCE reduction to c-DCE in 13 days under sulfate reducing conditions	Bagley and Gossett, 1990
Microcosms: 25 mL bottles filled with contaminated soil, voids filled with amended solution	Soils from photocopier refurbishing facility: concentrations not specified	Ethanol, Acetate, or Lactate with nitrate, sulfate, or yeast amendments	99% PCE reduction to c-DCE in 200 days under nitrate and sulfate reducing and methanogenic conditions: anoxic and anaerobic	Pavlostathis and Zhuang, 1993
Microcosms: 6 g sediment and 60 mL of medium in 124 mL bottles	Soil from Tinker AFB and Victoria TX spiked to 9 μM PCE	Methanol, formate, lactate, acetate, or sucrose	Up to 70% conversion to TCE and c-DCE to 200 days under various metabolic conditions	Gao, *et al*, 1997

Scholz-Muramatsu *et al*, (1989) used 50 mL of biomass culture from a biofilm reactor fed with benzoate. Benzoate was added to the 100 mL microcosms as the sole energy source and 2.8 mM PCE was added as the inoculum. Methanogenesis was selectively inhibited with bromoethane-sulfonic acid. c-DCE was the only transformation product measured in this test and formed in nearly the same concentrations in cultures with and without methanogenesis.

The uptake of benzoate was directly proportional to the c-DCE formed. In a similar study using anaerobic sludge (Bagley and Gossett, 1990), 600 μg/L of PCE was reduced to c-DCE in thirteen days. Lactate was used as a donor and methanogenic inhibitors were applied. Results showed reductive dechlorination of PCE proceeds under sulfate reducing conditions. Reductive dechlorination under both sulfate reducing and methanogenic conditions was also demonstrated in a study using anoxic/anaerobic field-contaminated soils containing PCE, TCE, and DCE (Pavostathis and Zhuang, 1993). Without electron donors the reductive dechlorination did not occur, however, with the addition of ethanol, acetate, or lactate dechlorination proceeded. Within 200 days, 99% of the PCE and TCE in the soils was reduced to c-DCE. Nitrate reducing conditions were also evaluated and did support dechlorination but at a much lower rate.

Multiple donor experiments were conducted and demonstrated PCE reduction while various levels of sulfate reducing, acetogenic, fermentative, and methanogenic activity was observed (Gao *et al*, 1997). Subsurface soils were collected from contaminated sites and tested with methanol, formate, lactate, acetate, and sucrose as donors. All substrates supported dechlorination to TCE and c-DCE, however, the lactate amended microcosm showed the most significant reduction of PCE. Though the results of this study do not demonstrate consistent dehalogenation rates, they do demonstrate the ability of indigenous microorganisms to degrade chloroethenes using a variety of anaerobic metabolisms. Collectively, these studies demonstrate the ability of microorganisms to anaerobically reduce PCE under a variety of metabolic conditions but all demonstrate the demand for an appropriate donor.

Reduction of Tetrachloroethene/Dichloroethene to Ethene and Ethane

Many researchers have demonstrated complete anaerobic reduction of PCE to ethene and ethane using microbial dechlorinators. More recently the problem of c-DCE accumulation at sites where the more rapid PCE and TCE reductions are complete, has resulted in greater attention being focused on the anaerobic reduction from the intermediate c-DCE. In the research reviewed (See Table 3.4), the selection of electron donors was critical to the success of many of the experiments. The following discussion only lists the donors that contributed to successful reduction. For further details on the other donors and nutrient amendments, see

the appropriate reference. This research predicts and in some cases actually demonstrates (Beeman *et al.*, 1994,Yager *et al.*, 1997, Becvar *et al.*, 1998) that complete in-situ dechlorination of contaminants without accumulation of toxic daughter products is possible.

Using standard 160 mL or 120 mL batch microcosm studies, complete reduction of PCE has taken from two to forty days (DiStefano *et al.*, 1991, 1992, Freedman *et al.*, 1989, Fennell and Gossett, 1997, Smatlak *et al.*, 1996, and Lorah *et al.*, 1997) and proceeded using a variety of electron donors. As early as 1989, anaerobic studies (Freedman *et al*, 1989) showed that by using methanol, hydrogen, formate, acetate or glucose as an electron donor, low concentrations of PCE and TCE could undergo 100% conversion to VC and ethene in less than three days under methanogenic conditions. Similar studies by DiStefano *et al.*, (1991, 1992) have also shown that by providing an adequate electron donor, high concentrations of PCE could be quickly reduced. In 1991 they demonstrated that by supplying methanol, 55 mg/L of PCE was 100% reduced to ethene in four days without methanogenesis. In 1992, they demonstrated 91 mg/L of PCE supplied at two day intervals could be completely reduced to VC and ethene within 14-40 days once a microbial population was established. In this study, researchers also demonstrated that it is the available hydrogen that is key to the reduction of chloroethenes and the metabolism of more complex donors serves to regulate the delivery of hydrogen. More recently, microcosm studies have also shown that PCE and TCE can be dechlorinated to ethene in 20 days and kinetics are directly affected by substate concentration (Nielsen and Keasling, 1998). By using groundwater from a PCE/TCE contaminated site and providing glucose as a substrate, complete reduction without accumulation of vinyl chloride was demonstrated. It was determined that for high PCE concentrations (>1 mg/L) degradation follow zero order kinetics while for low concentrations, degradation follows first order kinetics.

Fennell and Gossett, (1997) showed reductive dechlorination is dependant on the level of available hydrogen and that ethanol, lactate, propionate, and butyrate all served as effective hydrogen sources. The rate at which these donors provide hydrogen directly affects the conditions of dechlorination. If relatively high levels of hydrogen are produced, methanogens dominate while if the available hydrogen levels are kept low, reductive dechlorinators dominate without the production of methane. This competition for hydrogen by methanogens and reductive dechlorinators was also witnessed in a study using hydrogen

and formate as donors to successfully reduce 12 μM of PCE to ethene in only two days (Smatlak *et al*, 1996).

At an Aberdeen Proving Grounds site, sediments and groundwater were tested in microcosms to confirm in-situ dechlorination and to evaluate the potential for natural attenuation (Lorah *et al.*, 1997). With no additional donor added, complete removal of TCE and all daughter products was accomplished under methanogenic conditions. This indicated adequate donor supplies and capable microorganisms existed in-situ and natural attenuation is occurring.

Yang and McCarty (1998) demonstrated that dechlorination could be initiated on c-DCE and continued until it was completely reduced to ethene. Using benzoate and propionate it was shown that dehalogenators could use hydrogen at lower concentrations than methanogens or acetogens. The slower degradation of the propionate substrate provided hydrogen at a slow steady rate that favored greater dehalogenation than the benzoate that delivered adequate hydrogen to promote the competitive methanogens. When formate and acetate were provided in a mixed culture study (Windfuhr, 1998), microorganisms demonstrated the ability to completely dechlorinate c-DCE. Though successful dechlorination was observed, many inhibitors were also identified. These studies illuminate a promising outlook for the reduction of persistent c-DCE plumes, yet clearly establish the need to better understand the organisms involved in c-DCE reduction.

In an attempt to more closely mimic in-situ conditions, column microcosms have also been used to show complete reductive dechlorination is enhanced with the use of an electron donor (Carter and Jewell, 1992, DeBruin *et al*, 1992, Lee 1997, and Isalou *et al.*, 1998). In an expanded bed column with recycle (Carter and Jewell, 1992), it was shown that under methanogenic conditions, up to 12 mg/L of PCE could undergo 98% conversion to VC and ethene within three days when sucrose was supplied as a donor. Column operating temperatures in this study were maintained at 15 °C to simulate groundwater conditions. Using a fixed bed column to simulate passing groundwater through subsurface soils (DeBruin *et al*, 1992), it was shown that with lactate as a donor, 9 μM of PCE could undergo 100% conversion to ethane. PCE was no longer detected in the column effluent after two weeks and after 240 days no ethenes were detected in the column effluent. To further simulate groundwater conditions, the operating temperature of this column was reduced from

20 °C to 10 °C and operated in the dark. Complete conversion of PCE continued under these conditions. While exploring the potential for bioaugmentation (Lee et al., 1997), 30mg/L of PCE were shown to be completely dechlorinated, under methanogenic conditions, in less than eight days during column studies. During long term column testing, it was also demonstrated that 600 μM of PCE could be completely reduced in 17 hours (Isalou *et al.*, 1998). In a column that was operated for two and a half years under acetogenic conditions, PCE concentrations were raised from 12 μM to 600 μM while being supplied methanol as a substrate. For the first 21 months VC was the terminal endpoint. As acetogenesis became the primary metabolic pathway for methanol, ethene production began and continued through the remainder of the study.

As ultimate proof for complete in situ reductive dechlorination, a review of field studies was accomplished. In a field test in Victoria, Texas, PCE, TCE and DCE at 1700 μg/L, 535 μg/L, and 385 μg/L, respectively, were reduced to below detection limits in less than two years (Beeman *et al.*, 1994). Groundwater from a 450 square meter plot of land was continuously extracted from the down gradient side, augmented with benzoate and sulfate and injected up gradient under anaerobic conditions. Sulfate reducing conditions were allowed to dominate to control the production of VC, which is produced under methanogenic conditions, but not sulfate reducing conditions.

In-situ reductive dechlorination has also been observed at a New York site heavily contaminated with TCE, (Yager *et al.*, 1997). Though no donor has been added, it is believed there is an adequate supply of subsurface donors from co-contaminants to facilitate the reduction of TCE to ethene. Differing subsurface soil zones and groundwater migrations are currently retarding the complete dechlorination of all TCE, but enhanced bioremediation is being considered.

Table 3.4 Studies Demonstrating Reduction of PCE and DCE to Ethene and Ethane.

Test	Source Concentrations	Successful Donors See ref. for nutrients	Conclusions	Reference
Microcosms: 100mL suspensions in 160 mL bottles	PCE 0.5 mg/L TCE 1.0 mg/L repeated as depletion occurred	Methanol, Hydrogen, Formate, Acetate, or Glucose in digester sludge	100% conversion to VC, Partial to ETH in 3 days; methanogenic conditions	Freedman and Gossett, 1989

Test	Source Concentrations	Successful Donors See ref. for nutrients	Conclusions	Reference
Microcosms: 100mL suspensions in 160 mL bottles	PCE 55 mg/L at 2 day intervals	Methanol and yeast	100% Reduced to Ethene in 4 days w/o methanogenesis	DiStefano *et al.*, 1991
Microcosms: 100mL suspensions in 160 mL bottles	PCE 91 mg/L at 2 day intervals	Hydrogen or Methanol with yeast	Complete Reduction to VC and ETH within 14-40 days;acetogenic conditions.	DiStefano *et al.*, 1992
Microcosms: 100 mL of medium in 160 mL bottles	12 μM PCE	Hydrogen and Formate with yeast and butyrate	Complete reduction to ETH in 2 days; Demonstrated methanogen/ dehalogenator competition	Smatlak *et al.*, 1996
Microcosms: 100mL suspensions in 160 mL bottles	PCE 110 μM at 2 day intervals	Ethanol, Lactate, Propionate, or Butyrate with yeast	Comparable conversion to ETH with 4 different donors; methanogenic conditions	Fennell and Gossett, 1997
Microcosms: 162 mL bottles with ground-water and sediment	7.6 μM TCE	None: No donor supplied; field conditions applied	Complete reduction to ETH in 34 days; methanogenic conditions	Lorah *et al.*, 1997
Microcosms: 100 mL of medium in 160 mL bottles	5 μM *c*-DCE incrementally	Benzoate or propionate	Complete reduction to ETH; Dehalogenator advantage at lower hydrogen levels	Yang and McCarty, 1998
Microcosms: 120 mL vials	100 μM c-DCE	Formate, acetate and yeast	Complete reduction to ETH	Windfuhr, et al., 1998
Up-flow, 900 mL Continuous Flow Reactor	PCE 8-12 mg/L	Sucrose and yeast extract	98% Conversion to VC and ETH in 3 days at 15°C under methanogenic conditions	Carter and Jewell, 1992

Test	Source Concentrations	Successful Donors See ref. for nutrients	Conclusions	Reference
Fixed Bed Columns	PCE 9 μM	Lactate in Rhine River sediment with anaerobic sludge	100% Conversion to ETH in 240 days	DeBruin *et al.*, 1992
Column Studies	180 μM PCE	Not Specified	100% Conversion to ETH in 8 days under methanogenic conditions	Lee, et al., 1997
Columns: 16L Up-flow Continuous Feed; Long Term (2.5 yrs)	600 μM PCE	Methanol	Complete reduction within 17 hrs; Some residual 1,1 DCE under acetogenic conditions	Isalou, et al., 1998
In Situ Field Test, 3 feed wells, 3 extraction wells	PCE 1700 μg/L TCE 535 μg/L DCE 385 μg/L	Sodium Benzoate	All chlorinated ethenes reduced to BDL in 2 years under sulfate-reducing conditions	Beeman *et al.*, 1994
In Situ Biotrans-formation	TCE up to 20 mg/L	In-situ donor not identified; none added	Complete conversion to ETH in 6 months predicted through site modeling	Yager *et al.*, 1997
In Situ Treatability NAS Fallon	PCE <2130μg/L TCE <675μg/L DCE<2130μg/L VC<3.8μg/L	Lactate or Ethanol and benzoate; with yeast and vitamins	Initial results suggest reductive dechlorination and	Becvar *et al.*, 1998

Enhanced bioremediation is currently being field tested at a site in Nevada with encouraging indicators of in-situ reductive dechlorination (Becvar *et al.*, 1998). Five parallel test beds have been isolated in a former fire training pit. The beds are supplied with yeast, vitamins and either lactate or ethanol and benzoate. Though it is too early to show a direct correlation between decreasing parent chloroethenes and increased daughter products, initial indicators suggest an increasing anaerobic environment with overall chloroethene reduction.

Taken collectively, these studies clearly show that complete reductive in situ anaerobic dechlorination of chlorinated ethenes is possible. Results show that anaerobic reduction is

not limited to only the more highly chlorinated compounds, but will continue through all daughter products to produce ethene and ethane as the final products. Successful dechlorination at an acceptable rate for contaminated site remediation appears to be dependent on enhancement with an electron donor. Results show there is not one specific donor that works in all situations. The cumulative evidence suggests however, that the most promising choices of electron donors are short carbon chain alcohols such as ethanol and methanol or weak organic acids such as lactic, butyric, and propionic acids. The evidence also suggests that slow release hydrogenic substrates may be preferable to enhance dehalogenators and sustain in situ remediation. Studies also examined the effects of temperature and show that enhanced reductive dechlorination can be successful at typical groundwater temperatures of 10 to 15 °C. There is ample evidence from these studies to show the key to enhanced reductive dechlorination is identifying the most successful electron donor and possibly nutrient limitations for each site's conditions.

CHAPTER IV

EXPERIMENTAL APPROACH

SITE HISTORY AND CHARACTERISTICS

Operable Unit 1 is located on the eastern side of Hill Air Force Base in Northern Utah and contains groundwater that is heavily contaminated with chlorinated solvents from past disposal practices. Historically this piece of property has had many uses and contains a number of sites that functioned as on-Base disposal sites for fuels, oils and solvents. This list includes:

- Chemical Disposal Pits 1 and 2 used for industrial liquid waste disposal,
- Landfill 3 used for industrial liquid and solid waste disposal (dump and burn),
- Landfill 4 used for sanitary refuse disposal,
- Fire Training Areas 1 and 2 used to practice extinguishing aircraft fires,
- The Waste Phenol/Oil Pit used to dispose and burn waste oils and phenols, and
- A Waste Oil Storage Tank Site used to store waste fuels, fuel oil and hydraulic fluids.

These sites were in operation at various times from 1940 through the mid 1960s, and in some cases to the early 1970s at which time disposal and waste management practices were changed.

As a result of past practices, the contamination at this site is very complex and includes partially weathered or degraded fuels and solvents. Soil contamination includes PCE (up to 9,100 micrograms per kilogram [μg/kg]), TCE (up to 40,000 μg/kg), DCE (up to 14,000 μg/kg), and jet fuel (up to 42,100 μg/kg). Contamination also affects approximately seven acres of groundwater that are characterized by a floating layer of non-aqueous phase liquid (NAPL). This NAPL contains high concentrations of solubilized chlorinated solvents particularly TCE (up to 2,300 micrograms per liter (μg/L), DCE (up to 42,000 mL), and VC (up to 2,400 μg/L) (Montgomery Watson, 1995). PCE and TCE have been identified as wastes that were disposed of on-site. The DCE and VC were not identified as past waste and are presumed to be biodegradation products of PCE and TCE. Their presence indicates intrinsic bioremediation is occurring. Further review of data available in the 1995 RI/FS supports this conclusion and shows conditions are appropriate for intrinsic bioremediation in the Chemical Disposal Pit areas (CDP) of OU-1 (See Table 4.1). The decrease in dissolved oxygen, nitrate, and sulfate with a corresponding increase in dissolved iron and manganese in

the source area and immediately adjacent to the source area support the conclusion that the subsurface environment is highly reducing and capable of supporting reductive dehalogenation.

Table 4.1. Intrinsic Bioremediation Indicators

Intrinsic Bioremediation Indicators					
	Background: Upgradient from CDPs	CDP Area Averages Phase I&II RI & 1/4ly	Well U1-067: Source Area (1986-94)	Well U1-072 Adjacent to CDPs (1986-94)	Well U1-088: Downgradient from CDPs (1990-94)
Redox Potential (mV)	>-225		(-75- -100)	(-125- -150)	(-75- -100)
Dissolved Oxygen (mg/L)	>7		<1	1-2	1-2
Anions (mg/L)					
Bicarbonate	70-500	70-820	470	480	380-410
Alkalinity, Bicarbonate	255-849			485-642	260-303
Sulfate	0.96-58	ND-80.4	ND	0.3-11	0.37-8.4
Sulfide	ND-1	ND-1	1	0.1	ND
Chloride	39-99.6	35-370	56	43.2-79.5	43.8-51.6
Nitrate	0.88-5.8	ND-50	30	0.11-10	ND
Cations (μg/L)					
Dissolved Iron	ND-874	ND-43000	36000	17100-32300	465-3000
Dissolved Manganese	ND-251	ND-1810	820	582-960	59.6-960
VOCs (μg/L)					
Tetrachloroethene			ND	11	0.18
Trichloroethene			ND	94	ND
cis-Dichloroethene		ND-42000	42000	2700-9700	ND
Vinyl Chloride		ND-24000	2400	ND	ND
Ethene/Ethane/Methane	5	N/A	N/A	N/A	N/A

Past studies conducted by the United States Air Force provide a great deal of information on physical characteristics of OU-1. Surface soils consist of moderate to excessively well drained sand-silt mixtures imbedded with gravel and possessing moderately high to high permeability. The horizontal hydraulic conductivity of the site has been estimated to range from 0.0002 to 0.0004 centimeters per second while the calculated horizontal interstitial velocity ranges from 0.85 to 12.76 feet per day. Vertical hydraulic conductivity of the site ranges form 10^{-5} to 10^{-8} centimeters per second while vertical velocity ranges from 0.014 to 0.240 feet per year. Monitoring data show the ground water is moving primarily horizontally

across OU-1 and down the escarpment at the edge of the Base property with only minor vertical migration. (Montgomery Watson, 1995).

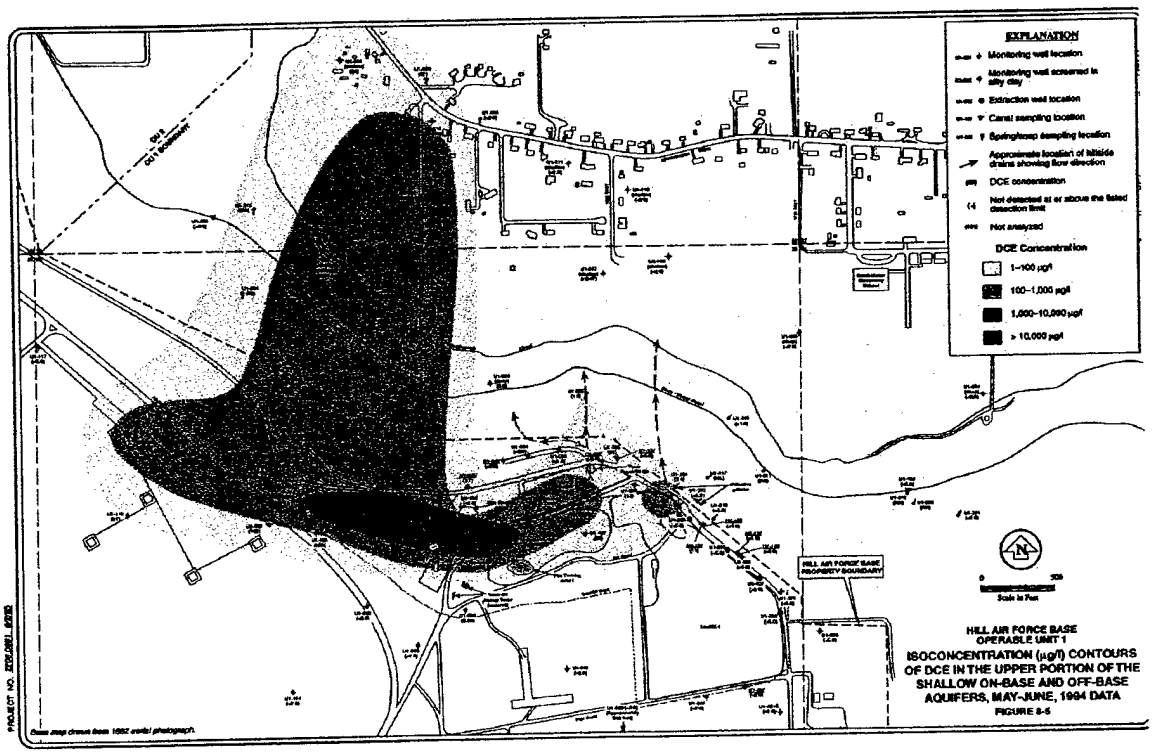

Figure 4.1. Hill AFB Operable Unit 1 Site Map

The stated worst-case contaminant levels are the maximum concentrations that have been found in the source area identified as the Chemical Disposal Pits. Any proposed remediation technology or implementation of the RABITT approach would involve treatment of much lower contaminant levels. Degradation and dissolution within the source area as well as in the area between the source area and treatment area will result in lower, more manageable concentrations that could be treated by an in situ bioremediation system. A review of chlorinated solvent plumes at Hill AFB in 1997 (Graves, *et. al.*) concluded that natural attenuation mechanisms at OU-1 are not limited to reductive dehalogenation. Other mechanisms include volatilization through the vadose zone, evapotranspiration occurring by capture of the groundwater on the hill slope by the root zone, and discharge of the shallow groundwater through seeps and springs.

The dichloroethene is of particular concern at OU-1 not only because it significantly exceeds the drinking water standards near the source of contamination, but also because it is

detectable in the groundwater over an area that covers 193 acres as shown in Figure 4.1 (Montgomery Watson, 1995). Incomplete dechlorination of this compound could result in the accumulation of significant levels of the more toxic vinyl chloride, a known carcinogen. Therefore, complete and rapid dechlorination of all chloroethene compounds is essential to successful remediation of OU-1. The 1998 Proposed Plan of action for remediation of OU-1 clearly demonstrates that partially due to past corrective actions, the c-DCE plume is shrinking, however, even with the proposed additional corrective action the estimated restoration timeframe for the source area is 50+ years and 12 years for the non-source area. Enhancing the bioremediation occurring on-site could significantly reduce these timeframes and greatly reduce any potential future health concerns.

EXPERIMENTAL DESIGN

By understanding the stoichiometry of chemical and biological reactions, we can anticipate changes in microbial environments. Microorganisms obtain energy for growth and maintenance by removing electrons from donors and transferring them to electron acceptors. When the donor or acceptor concentration is deficient, microbial activity is limited. Under anaerobic or microaerobic conditions and when an adequate donor concentration is available, chloroethenes can act as microbial substrates while serving as respiratory electron acceptors. As these microorganisms grow, the rate of substrate utilization is directly proportional to the mass of the microbial population mediating the reaction:

$$r_{su} = -kX\,(S/(K_s + S)) \quad (1)$$

$$r_g = YkX\,(S/(K_s + S)) - Bx \quad (2)$$

$$\mu = Yk\,(S/(K_s + S)) - b \quad \text{(Monod, 1942, van Uden, 1967)} \quad (3)$$

where: r_{su} = rate of substrate utilization, gS/l-day
k = maximum substrate utilization rate, gS/gX-day
X = biomass concentration, g/l
S = rate-limiting substrate concentration, mg/L
K_s = Monod constant; half-velocity coefficient, mg/L
r_g = rate of microorganism growth
Y = Yield coefficient, gX/gS
b = decay coefficient, day^{-1}
μ = specific growth rate, day^{-1}

According to these equations, the concentration of microorganisms will increase if the substrate concentration is in excess of the rate of decay. By providing excess donor in the form of organic compounds, naturally occurring electron acceptors will be depleted and microorganisms capable of discharging electrons to other available acceptors gain a selective advantage. As this proceeds, biologically active zones can be established which accelerate the rate of reductive dechlorination and growth of halorespiring microorganisms. With excess electron donor, the chloroethene electron acceptors become the limiting substrates and conditions are optimized for their effective biotransformation.

In the case of column reactors, macroscopic transport of chloroethenes can be characterized by a 1-D advection/dispersion/sorption/reaction equation:

$$\varepsilon\,(dS/dt) = D_H(d^2S/dX^2) - V\,(dS/dX) - aJ + QS \qquad (4)$$
$$= \text{dispersion} - \text{advection} - \text{reaction} + \text{the source}$$

where: ε = porosity
S = substrate concentration
t = time
D_H = Diffusion coefficient
X = Biofilm thickness
V = Specific Discharge at Darcy Velocity
a = surface area
J = Flux in the biofilm layer
Q = Flowrate

By solving these coupled equations for each chloroethylene, key kinetic parameters for the reduction of chloroethenes can be predicted and a process model can be developed for field application.

MATERIALS AND METHODS

Soil Collection

Soil samples were collected in the Hill Air Force Base source area identified as Chemical Disposal Pits number 1 and 2. All soils were collected using a hollow stem auger drill with split-spoon samplers. Samples were collected at depths ranging from 29 to 33 feet below ground surface. This depth is characterized by a sandy/gravel formation that comprises the saturated zone just above a clay layer. To minimize exchange with the atmosphere, cores were transferred from the split spoons in the field and immediately placed in sterile 1 quart

glass Mason™ jars containing groundwater from the same hole used to collect soil samples. Groundwater in the jars was allowed to overflow as the soil was added and all jars were capped with Teflon™ lined lids as described in the RABITT protocol (Morse *et al.*, 1998). Soil jars were maintained under anaerobic conditions at 4° C for approximately six-months prior to assembling microcosms. Soils were characterized by a black oily appearance and strong hydrocarbon odor.

Preliminary soil respirometry testing was completed to verify the viability of these soils. (See Appendix A for Respirometry Protocol). Respirometers were assembled in an anaerobic glovebox with a 95% N_2/5% H_2 atmosphere and purged with nitrogen prior to being removed from the glovebox. Regardless of efforts to limit oxygen introduction, respirometers were not maintained anaerobically. Respirometry tests proceeded under microaerobic conditions. Results of testing showed carbon dioxide production in nearly all respirometers and methane production in n-propanol amended respirometers. Results of this testing suggested an active, indigenous microbial population and viability of these soils for the electron donor study.

Aquifer Sampling

Groundwater supplied to all the microcosms was collected from OU-1 Dewatering Well # U1-201, immediately adjacent to the Chemical Disposal Pits. This well is 31 feet deep and screened from 20-30 feet below ground surface and located approximately 50 feet to the East of the site used for soil collection. Well #U1-201 has a submerged pump to deliver groundwater to the leachate collection system that transports water to the Industrial Waste Treatment Plant (IWTP). The well head is equipped with a faucet that is pressurized due to backpressure in the leachate collection system. Water was collected from this faucet using a Tygon™ hose dedicated for this purpose. To minimize mixing with the atmosphere, the water flow rate was kept very low and the hose outfall was maintained at the bottom of the twenty-liter collection bottle until it overflowed. The bottle was sealed with no headspace using a rubber stopper and Parafilm® and immediately transported to the laboratory. In the laboratory the water was stored at room temperature (19° C) in the dark until it was separated into unamended control water and nutrient amended water bottles which were installed in-line in the microcosm apparatus. Water was collected from Well #U1-201 approximately

every seven days. The water was slightly greenish/yellowish in appearance with a noticeable hydrocarbon sheen. Occasionally globs of brown oily materials were present in the water.

Donor Selection

Electron donors were selected based on the literature review and each chemical's ability to release diatomic hydrogen (See Appendix B). Fatty and aromatic acids, an alcohol and an aromatic hydrocarbon were chosen to allow a broad examination of the potential to enhance dechlorination. In specific, lactic acid, benzoic acid, n-butyric acid, and toluene were obtained from Fisher Scientific Co. (Fairlawn, NJ) while n-propanol and propionic acid were obtained from Mallinckrodt Baker Inc. (Paris KY). These donors supply electrons according to the oxidation half reactions defined in Table 4.2. The candidate donors were selected based on their ability to supply some of their H_2 equivalents in low-energy, low-rate biochemical reactions. The moles H_2 per electron equivalent of the selected donors and final donor concentrations are shown in Appendix B and C.

Table 4.2. Electron Donor Oxidation Half Reactions

Electron Donors Selected	ΔG^o (kJ/eequiv)
n-Propanol $1/18\ CH_3CH_2CH_2OH + 5/18\ H_2O = 1/6\ CO_2 + H^+ + e^-$	-31.42
Propionic Acid $1/14\ CH_3CH_2COO^- + 5/14\ H_2O = 1/14\ HCO_3^- + 1/7\ CO_2 + H^+ + e^-$	-27.88
Lactic Acid $1/12\ CH_3CHOHCOO^- + 1/3\ H_2O = 1/12\ HCO_3^- + 1/6\ CO_2 + H^+ + e^-$	-32.94
Butyric Acid $1/20\ CH_3CH_2CH_2COO^- + 7/20\ H_2O = 1/20\ HCO_3^- + 3/20\ CO_2 + H^+ + e^-$	-17.63
Benzoic Acid $1/30\ C_6H_5COO^- + 13/30\ H_2O = 1/30\ HCO_3^- + 1/5\ CO_2 + H^+ + e^-$	-28.84
Toluene $1/36\ C_7H_8 + 14/36\ H_2O = 7/36\ CO_2 + H^+ + e^-$	-28.15

As previously stated the reduction of the chloroethenes in microcosm studies and field evaluations has been dependent upon an adequate supply of substrate. Operable Unit 1 soils and groundwater are characterized by very high levels of dichloroethene. To provide complete remediation, the calculated electron equivalent demand was based on the premise that all existing species of chloroethenes would need to be completely reduced to ethene. To ensure an adequate supply of the electron donors, the predicted electron equivalents demand

was based on worst case chloroethene concentrations at OU-1. The calculated electron equivalent demand was then increased by a safety factor of four (See Appendix D). To stimulate microbial dehalogenation in the continuous flow microcosms, butyric acid, lactic acid, propionic acid, and n-propanol solutions were supplied at approximately 2% of the total flow while benzoic acid and toluene solutions were supplied at approximately 8% of the total flow. Differences in supply rates were based on solubility limits of benzoic acid and toluene.

Microcosm Configuration and Assembly

Continuous upflow soil columns were designed to simulate subsurface conditions characteristic of OU-1. A schematic of a single column reactor is shown in Figure 4.2, however, the full system included eight parallel columns and is shown in Figure 4.3. Each column contained a lower layer of soil and an upper layer of OU-1 groundwater. All columns were operated in the dark at 19° C throughout the experiment and received continuous flow of the same OU-1 source groundwater, amended differently for each microcosm. The groundwater supply was amended with Resazurin® (Sigma Chemical Co, St Louis, MO) as an indicator of low redox potential (<1 mg/L to avoid toxicity). With the exception of one column receiving only groundwater, the columns also received yeast extract (Sigma Chemical Co, St Louis, MO), $NaHCO_3$ (Sigma Chemical Co, St Louis, MO) as a buffer, and vitamins. The yeast extract was supplied in low doses (20 mg/L) while the water was buffered with 1g/L to maintain an alkalinity of 300-1500 mg/L as $CaCO_3$. Improper buffering between days 59 and 166 did not affect alkalinity, however, during this period the pH in all vitamin amended columns ranged from 8.5 to 9.0. Vitamins were supplied according to the draft RABITT protocol recipe (Morse *et al.*, 1997) and listed in Table 4.3.

On experiment day 134, spiking of the groundwater supply began to compensate for near non-existent levels of c-DCE in the water collected from Well #Ul-201. After start up of all columns, the water from Well #U1-201 showed a progressive and drastic reduction in c-DCE concentrations. Spiking to approximately 1000 µg/L c-DCE (Supelco, Bellefonte, PA) was attempted based on average concentrations of c-DCE found in monitoring wells in and around Chemical Disposal Pits 1 and 2 (Montgomery-Watson, 1995). Difficulties in mixing c-DCE into the water in the feed reservoirs resulted in actual c-DCE concentrations ranging from 150-663 µg/L. Spiking with c-DCE continued throughout the remainder of the study.

Table 4.3. Vitamin Concentrations Used in Microcosm Study

Constituent (Morse, 1997)	Quantity (mg/L)	Chemical Supplier
d-biotin	20	Sigma Chemical Co, St Louis, MO
Folic acid	20	Fisher Scientific Co. Fairlawn, NJ
Pyridoxine hydrochloride (B_6)	100	Fisher Scientific Co. Fairlawn, NJ
Thiamin hydrochloride (B_1)	50	Sigma Chemical Co, St Louis, MO
Riboflavin (B_2)	50	Eastman Kodak Co, Rochester, NY
Nicotinic acid	50	Aldrich Chemical Co, Milwaukee, WI
DL-calcium pantothenate	50	Sigma Chemical Co, St Louis, MO
Vitamin B_{12} (cyanocobalamin)	10	Sigma Chemical Co, St Louis, MO
p-aminobenzoic acid	50	Sigma Chemical Co, St Louis, MO
Lipoic acid	50	Fisher Scientific Co. Fairlawn, NJ

Other than the c-DCE spiking, columns were supplied with three combinations of ingredients. One column received only unamended groundwater and served as a background reactor simulating current groundwater conditions. One column was supplied with OU-1 groundwater containing Resazurin®, buffer, vitamins and yeast extract but no electron donors. This column served as both the background reactor to evaluate the effects of nutrients and as a control for electron-donor-augmented reactors. The remaining columns were supplied groundwater, Resazurin®, buffer, vitamins, yeast extract, and an electron donor solution provided according to values shown in Table 4.4. See Appendix E for donor delivery calculations based on actual Total Organic Carbon (TOC) analysis.

Table 4.4. Electron Donor Supply Values

Electron Donor	M.W.	Supply Line I.D. (mm)	Flow Rate (ml/min)	Total Flow (ml/min)	Donor % of Total Flow	Donor Supply (mg/L)	Total Donor (mg/L)	Molar Concentration (mM)
n-Butyric Acid	88.10	0.19	0.0044	0.235	1.87	8536.63	159.8	1.814
Benzoic Acid	122.12	0.38	0.0190	0.233	8.15	2180.71	177.7	1.455
Lactic Acid	90.08	0.19	0.0044	0.244	1.80	7882.00	142.1	1.578
Propionic Acid	74.08	0.19	0.0044	0.223	1.97	5658.89	111.7	1.507
n-propanol	60.09	0.19	0.0044	0.231	1.90	3672.17	69.9	1.164
Toluene	92.13	0.38	0.0190	0.234	8.11	72.55	5.9	0.064

By examining the chemical oxygen demand (COD) associated with c-DCE, we also confirmed these TOC levels represent an excess of electron equivalents. Eight milligrams of COD is equivalent to 1.0 milliequivalent (mequiv) of electrons and four mequiv of electrons are required for the reduction of 1 mM of c-DCE to ethene. Therefore, a minimum of 32 mg/L of COD is required for the reduction of 1 mM or 97 mg/L of c-DCE to ethene. Assuming only 10% of the electrons are available for reductive dehalogenation (McCarty,

1998), 320 mg/L would be required. The COD to organic carbon ratio for organic material is typically 2.5 to 3.5; the amount of TOC equivalent to achieve the reduction of 1 mM of c-DCE would be on the order of 90 to 130 mg/L COD. For the 1000 ppb c-DCE spiking goal, these values would range from 0.93 mg/L to 1.34 mg/L. Analytical results show that all donors were supplied well in excess of these values (See Appendix E).

Groundwater collected as previously described was mixed and added to the system approximately every seven days. Unamended and amended feed reservoirs were drained and refilled each time water was needed to ensure consistency in the water provided to all columns. Fresh donor supplies were mixed and installed at intervals not exceeding 30 days.

The system used in this study had three primary components: a feed assembly, the columns, and an effluent assembly. With the exception of the manifold tubing in the peristaltic pump, donor feed line, and sampling septums, all components were stainless steel, glass, or Teflon™ to avoid incompatibilities with chlorinated compounds and to limit sorption and volatilization losses (See Appendix F for Materials Inventory).

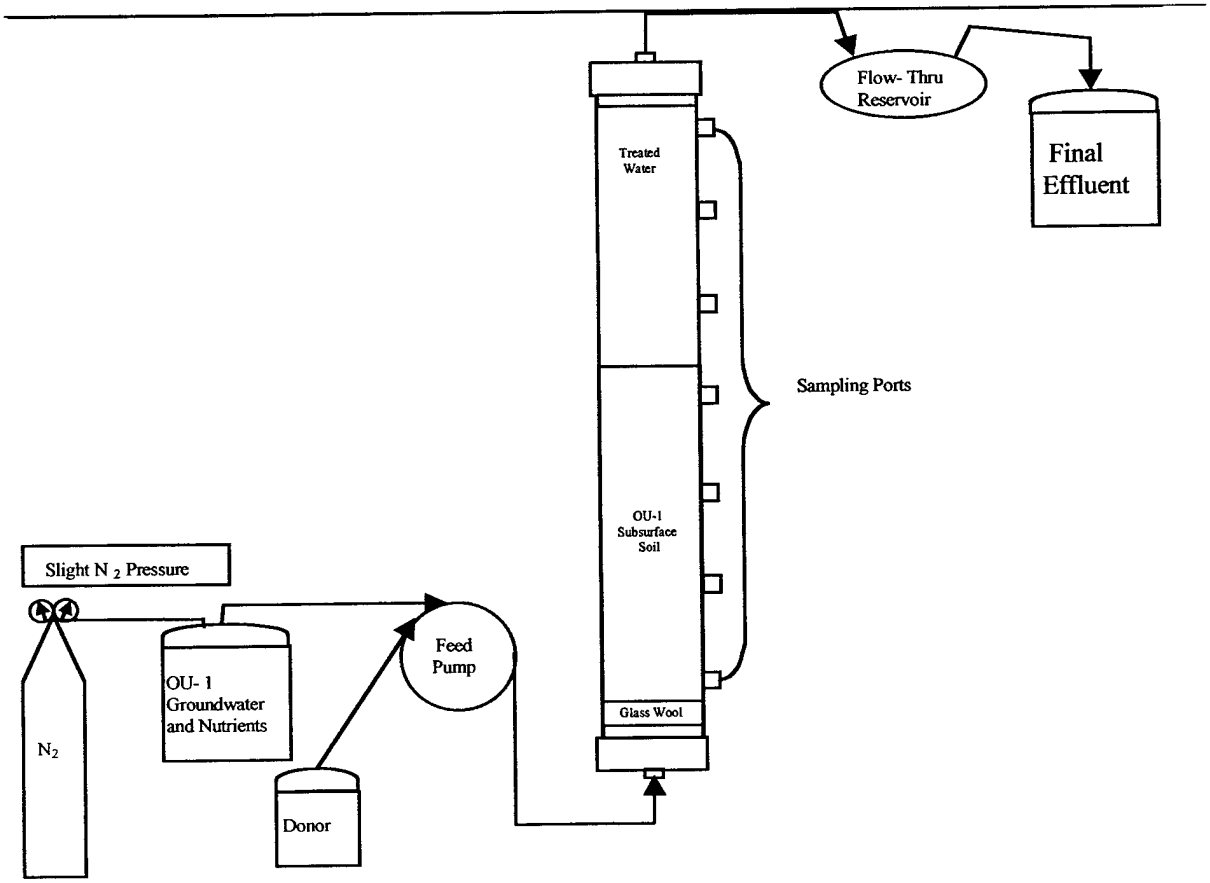

Figure 4.2. Single Column Schematic

The feed assembly consisted of the groundwater reservoirs and 1L-donor solution bottles, a nitrogen headspace system for the influent reservoirs, the pump and the associated fittings. Nitrogen was supplied to the groundwater reservoirs at just above atmospheric pressure to

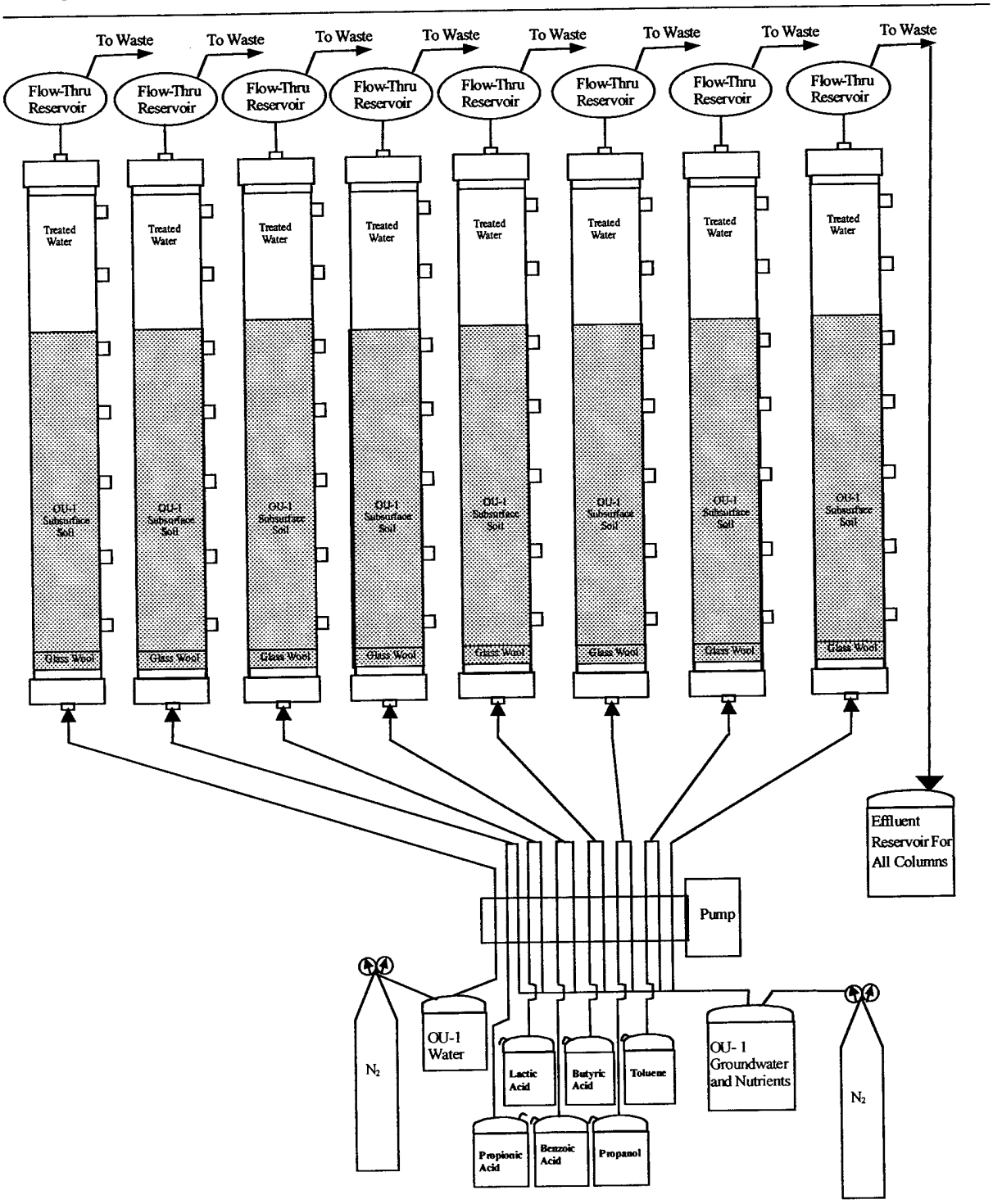

Figure 4.3. Full System Schematic

provide an inert head on the feed bottles and compensate for the vacuum created as the water was pumped from the bottles. Donor bottles were fitted with pressure compensation lines to allow stabilization with atmospheric pressure while controlling the potential entry of foreign materials into the bottles. A multichanneled (Watson-Marlow Model 205U) peristaltic pump, operated at 3 rpm was used as the sole driver for all groundwater and donor solutions and provided flow (0.233+/-0.011 mL/min) at a rate reflective of the hydraulic conductivity encountered in OU-1 (0.045cm/min (0.221mL/min)) (Montgomery -Watson, 1995). See Appendix G for predicted and measured HRTs and flow calculations. Groundwater supplied through 1.42 mm ID manifold tubing (Watson-Marlow #978.0142.000) and donor solutions were combined prior to entering the columns. Butyrate, lactate, propionate, and propanol were supplied through 0.19 mm ID manifold tubes (Watson-Marlow #984.0019.000) while benzoate and toluene were supplied through 0.38 mm ID manifold tubes (Watson-Marlow #984.0038.000) to compensate for lower solubility levels. Immediately after combining, all solutions were pumped through the base of the vertical columns.

The microcosm columns were glass liquid chromatography columns (Ace Glass, Inc #5820-37) measuring 25 millimeters ID and having a useable length of 600 millimeters. All columns were fitted with a vertical series of ¼ inch glass sampling ports with rubber septa to facilitate profile sampling. Each column contained a lower layer of grossly contaminated soil supported by 1 centimeter of glass wool (Alltech Associates, Inc) and an upper layer consisting of OU-1 groundwater percolated through the soil. The soil layer was 46 centimeters +/- 2.5 centimeters in depth. The slight difference in soil depths has been attributed to a variance in settling after column assembly. Soil homogenization and column assembly took place in an anaerobic glovebox (95%N_2/5%H_2) to avoid adding oxygen to the soils. After assembly, microcosms were sealed and removed from the glovebox. Seals were interrupted only long enough to allow connection within the full microcosm system.

The effluent from each column passed through an in-line effluent reservoir prior to disposal. The 40-mL reservoir served a dual purpose: this reservoir bottle filled with effluent water provided an air tight seal to the effluent end of each reactor and provided fluid for temporary back flow to compensate for the sample volume removed during sampling. Final effluent from these reservoirs was collected in a single waste reservoir that was returned to Hill AFB and disposed of through the Industrial Wastewater Treatment Plant.

Analytical Method

The parameters of concern for this project are defined in Table 4.5 along with their respective analytical method of measurement. Each microcosm was sampled for volatile organics, pH, dissolved oxygen content, and alkalinity after a thirty-day acclimation period. Influent samples were collected directly from the unamended and amended groundwater reservoirs using a 25-milliliter pipette. Effluent samples for all columns were collected from the upper most sampling port on the microcosm using 50-mL syringes equipped with 18 gauge needles. Samples were slowly transferred to beakers or sample vials in a manner minimizing possible aerobic mixing. Dissolved oxygen, pH and alkalinity were then sampled on a weekly basis throughout the remainder of the experiment. Volatile organic compounds (VOC) were sampled once every three weeks for the first 15 weeks of the experiment and then every week for the remaining nine weeks in which DCE spiking occurred. All VOC samples were collected in 44mL VOA vials and preserved for transportation to the laboratory using 0.4 mLs of a solution containing 0.1 mg/L sodium azide (J.T. Baker Chemical Co, Phillipsburg, N.J.).

Table 4.5. Analytical Parameters

Parameter	Analytical Methods	Performed By:
PCE TCE c-1,2-DCE, t-1,2-DCE 1,1-DCE VC	SW846 Method 8260B	Hill AFB Environmental Chemistry Laboratory (TIEL)
Ethene, Ethane, Methane	Kampbell *et al.*, 1998	Hill AFB TIEL
Chloride	EPA Method 300	In-House; UWRL
TOC	EPA Method 5310C	American Analytical
Alkalinity	AWWA Method 2320B	In-House
pH	Ion Selective Electrode	In-House
Dissolved Oxygen	DO Probe	In-House

Samples were collected on a weekly basis and analyzed for pH, dissolved oxygen and alkalinity. The pH and dissolved oxygen were analyzed using a direct reading Accumet AR50 (Cat#13636AR50) Dual Channel pH/Ion Conductivity meter with a AccTupH probe (Cat# 13-620-181) and a dissolved oxygen probe (Cat# 970899). Alkalinity was determined using the titration method described in Standard Methods, 17th edition.

Concentrations of chlorinated organics were determined by their chromatographic mobility and their mass spectral fragmentation using EPA Method SW8260 with purge and trap. Prior to analysis, the samples were purged with helium for 12 minutes at 30°C while headspace gases were collected on a 25 cm x 0.267 cm I.D. Tekmar #3 diphenyl oximer polymer with silica gel and coconut charcoal trap. After four minutes desorbing at 225° C, a 5 mL aliquot was introduced through a splitless injection port into a Finnigan Mat -Incos 50 XL gas chromatograph/mass spectrometer (GC/MS). A 75m x 0.53mm ID Mega Bore capillary column coated with DB 624 (J&W Scientific) was installed on the GC. The system was temperature programmed as follows: hold at 5°C for 10 minutes and ramped to 145°C at 8°C per minute. The system was then elevated to 225°C for 6 minutes to drive off water vapor and heavier analytes.

Concentration of ethene, ethane, and methane were determined using a headspace equilibrium method described by Kampbell and Vandegrift (1998). Prior to analysis the samples are allowed to equilibrate to room temperature and inverted. A 10-mL aliquot was removed by inserting a needle attached to a gas tight syringe through the septa. A second needle connected to a supply of helium at ambient pressure was inserted through the septa. As the sample water was removed, helium was allowed to fill the 10 mL headspace and a 100 ul aliquot of headspace was drawn into a gastight syringe and injected into a Perkin-Elmer Model 8400 capillary gas chromatograph (GC) equipped with a flame ionization detector (FID). A 25m x 0.53mm ID plot fused silica Pora Plot Q column was installed on the GC. The system was temperature programmed as follows: hold at 30°C for 4 minutes and ramped to 150°C at 30°C per minute to drive off water vapor and heavier analytes. Methane, ethene and ethane eluted at 0.7, 1.5, and 2.0 minutes respectively. Analyte peaks were integrated and concentrations were calculated by comparing to standard curves.

CHAPTER V

RESULTS AND DISCUSSION

The c-DCE removal efficiencies and related discussion of this experiment are presented in this chapter. The discussion is organized to address the project objectives including: 1.) demonstrating complete reductive dechlorination of *cis*-DCE without accumulation of VC is possible under microaerobic conditions using OU-1 soil and groundwater, 2.) comparing various electron donors and determining the most promising donor(s) for maintaining dechlorination under OU-1 site conditions, 3.) determining if vitamin and yeast amendments are necessary for complete dechlorination in OU-1, and 4.) demonstrating a cost-effective alternative for remediation of chloroethenes at OU-1. To address objectives, examination of c-DCE removal efficiencies is followed by a comparison of removal in unamended and amended columns as well as the columns supplied with donors. By examining the data (See Appendix H for analytical results) some interesting reactions other than those involving chloroethenes were identified. These are discussed at the end of this chapter.

CHLOROETHENE DECHLORINATION EFFICIENCIES IN LABORATORY COLUMNS

Removal efficiencies of c-DCE in all columns encompassed a wide range and were very inconsistent. By reviewing Table 5.1, it is apparent that not only is the c-DCE removal efficiency highly variable it appears that at times c-DCE is produced within the columns.

Table 5.1. *cis*-Dichloroethene Percentage Removal Efficiencies (Influent vs Effluent)

Experiment Day	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
31	11.41	4.35	6.76	8.40	7.35	10.12	6.05	8.21
52	-10.04	2.11	5.74	11.25	3.28	8.36	14.81	10.13
72	11.84	10.26	13.57	19.12	18.56	9.07	12.90	19.33
93	15.04	1.14	-2.24	8.08	15.10	16.20	5.80	-3.61
115	61.69	9.01	12.76	16.84	-81.72	18.88	5.27	18.20
136	29.78	22.50	21.86	34.49	20.77	33.22	28.33	25.27
143	33.48	14.92	19.71	23.49	16.37	0.99	9.63	9.63
150	-4.02	25.33	19.95	33.74	18.34	32.09	18.99	17.03
158	49.82	-68.44	-151.79	-123.05	-146.55	-134.64	-93.14	-179.16
165	51.58	14.33	14.73	21.80	22.39	21.49	21.21	27.86
171	-1.45	3.05	-0.16	0.02	0.69	37.76	1.12	10.78
178	-0.44	-0.06	0.18	10.14	3.39	2.92	7.22	12.50
185	-11.95	-0.47	5.19	21.30	3.33	10.59	11.96	14.52
192	13.76	69.35	3.47	13.78	9.47	3.47	14.89	12.08
199	7.31	4.19	6.39	12.15	9.81	5.65	3.52	6.17
Range	-10/62%	-68/69%	-152/22%	-123/34%	-147/22%	-134/38%	-93/28%	-179/25%

For VC and other compounds discussed, sample results that showed concentrations below detection limits were assigned "apparent" removal efficiencies by assuming the sample concentration was zero. In sample sets with a detectable influent concentration and an effluent concentration below detectable limits, an apparent removal efficiency of 100% was assigned. In sampling events where the influent value was below detectable limits, an apparent removal efficiency of zero has been assigned. In some cases, assuming a zero concentration may hide production of some compounds during a sampling event, however, even by applying production values greater than 200%, the relationship between average removal efficiencies of any compound examined does not change.

In Table 5.2, vinyl chloride apparent removal efficiencies are presented to address the issue of accumulation resulting from the dehalogenation of c-DCE. In most cases, VC accumulation was demonstrated at decreasing levels until day 115 at which time all columns began showing zero accumulation. Zero accumulation continued through the remainder of the experiments. All removal efficiency values of zero in Table 5.2 reflect the "apparent" removal efficiencies and demonstrate no accumulation or reduction of VC.

Table 5.2. Vinyl Chloride Apparent Removal Efficiencies

Experiment Day	Unamended Groundwater Effluent (Col 1)	Nutrient/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
31	8.44	-7.42	-6.96	-10.78	-5.07	-8.75	-10.99	-14.69
52	-109.20	-95.38	-95.38	-72.88	-89.48	-61.56	-36.50	-92.58
72	0.00	-17.24	-43.02	-15.80	-16.20	-31.22	-28.22	-10.65
93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
115	0.00	100.00	-21.45	-9.54	-96.54	-4.17	-8.46	-8.70
136	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
143	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
150	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
158	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
165	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
171	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
178	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
185	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
192	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
199	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Range	-109/8%	-95/100%	-95/0	-72/0%	-97/0%	-62/0%	-37/0%	-93/0%

Chloroethene-DCE Degradation in the Absence of Additives

Removal of c-DCE and VC in the unamended column varied widely and did not demonstrate a consistent pattern (See Figure 5.1). Removal efficiencies for c-DCE ranged

from -10% to 62% including five sampling events that appeared to demonstrate accumulation or production of c-DCE, five sampling events that demonstrated removal at greater than 20%, and five sampling events that demonstrated removal between zero and 20%. Removal efficiencies for VC ranged from -109% to 8%, however, most sampling events did not identify VC at detectable concentrations.

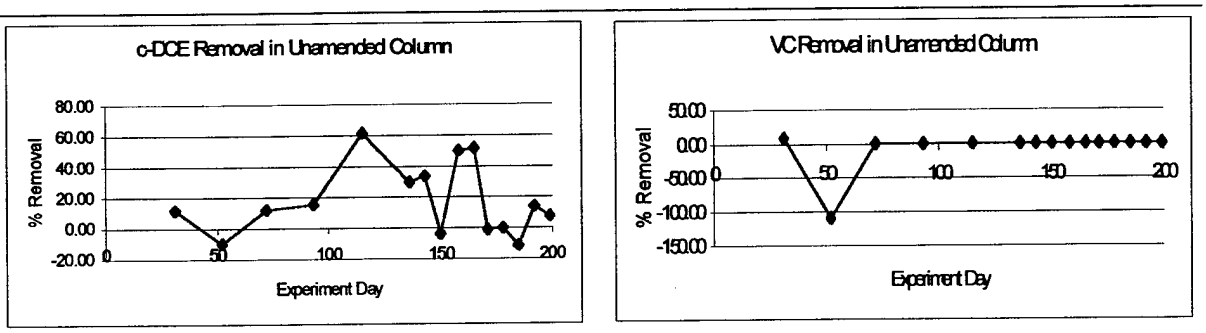

Figure 5.1. Chloroethene Removal Efficiencies in the Unamended Column

Chloroethene Degradation in the Presence of Vitamins and Yeast

Removal efficiencies for c-DCE and VC in the vitamin and yeast amended column covered a wide range and did not present a consistent trend (See Figure 5.2). The c-DCE removal efficiencies ranged from -68% to 69% including three sampling events that demonstrated the accumulation or production of c-DCE, three sampling events that represented greater than 20% removal, and nine sampling events that represented removal efficiencies between zero and 20%. VC removal efficiencies ranged from -95% to 100% and included 11 sampling events that had less than detectable levels of VC.

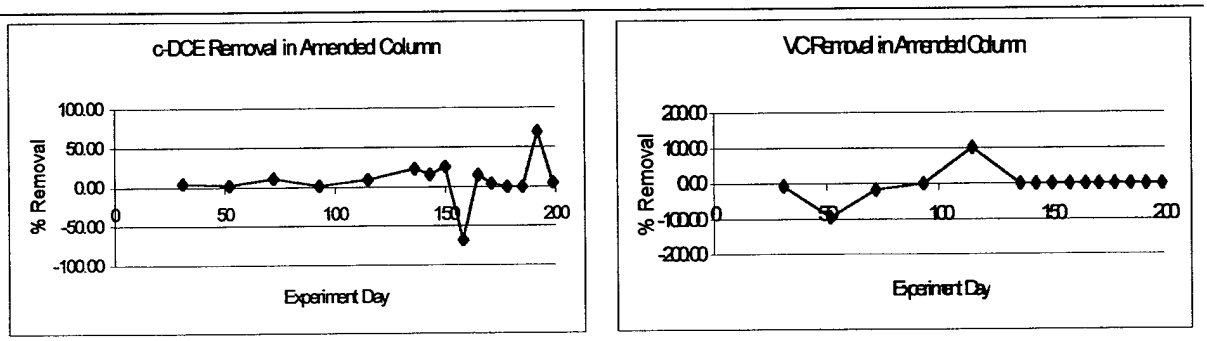

Figure 5.2. Chloroethene Removal Efficiencies in the Vitamin and Yeast Amended Column

Columns Amended with Electron Donors

Six columns received continuous feed of a specified electron donor in addition to the vitamin and yeast amendments and are individually discussed below. A review of c-DCE results shows a wide range of removal efficiencies with a notable event occurring on day

158. Results for that sampling event show all columns receiving amendments had considerably higher c-DCE levels in the effluent than in the influent water (See Appendix H for c-DCE removal rates and average rates excluding day 158 results). VC removal efficiencies also varied greatly during periods of VC accumulation, which were followed by less than detectable VC concentrations in all columns.

Chloroethene Degradation in the Presence of n-Butyric Acid

The n-butyric acid column removal and apparent removal efficiencies for c-DCE and VC ranged from -152% to 22% and -95% to zero respectively (See Figure 5.3). Removal of c-DCE included three sampling events that demonstrated apparent production, nine sampling events that demonstrated between zero and 20% removal, and one sampling event that demonstrated higher than 20% removal. The VC removal efficiencies varied during the initial period of VC accumulation and eleven on the sampling events showed no detectable VC in the influent or effluent.

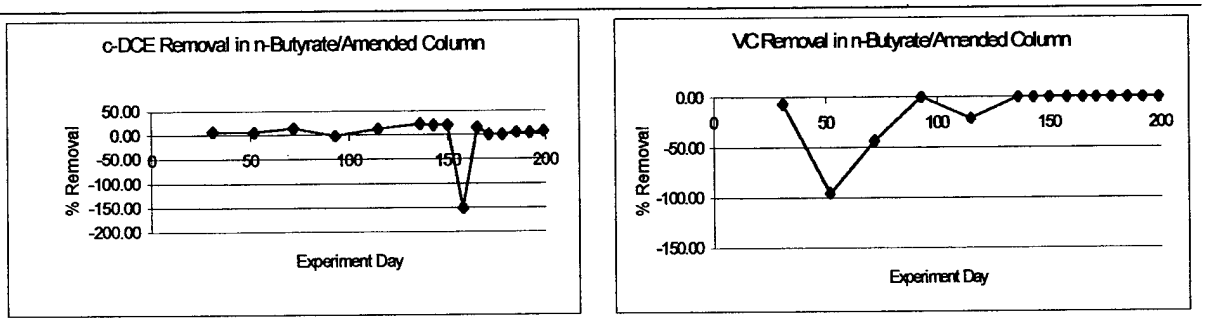

Figure 5.3. Chloroethene Removal Efficiencies in the n-Butyric Acid/Amended Column

Chloroethene Degradation in the Presence of Benzoic Acid

Removal and apparent removal efficiencies for the column supplied with benzoic acid were -123% to 34% and -72% to zero for c-DCE and VC respectively (See Figure 5.4). The

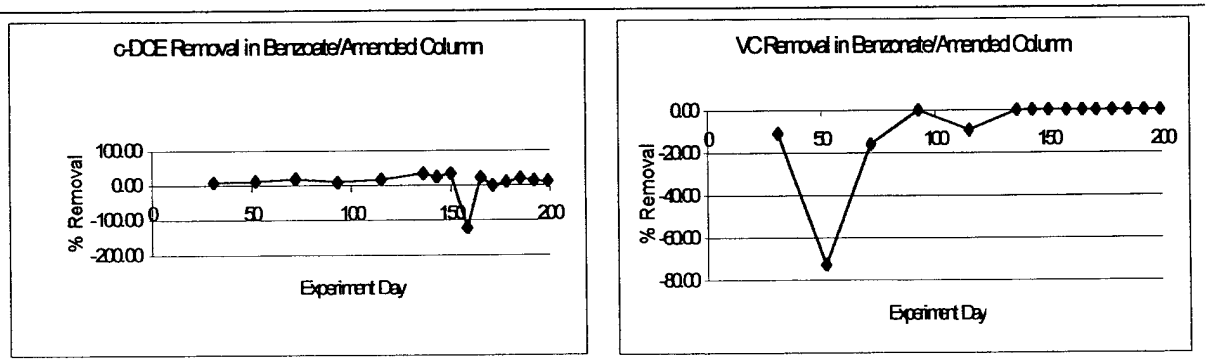

Figure 5.4. Chloroethene Removal Efficiencies in the Benzoic Acid/Amended Column

only sampling event that demonstrated an apparent production of c-DCE was on day 158. Nine sampling events demonstrated zero to 20% c-DCE removal while five sampling events demonstrated greater than 20% c-DCE removal. Four sampling events demonstrated the accumulation of VC while eleven sampling events showed no detectable VC.

Chloroethene Degradation in the Presence of Lactic Acid

Chloroethene removal and apparent removal efficiencies in the column supplied with lactic acid were also widely varied (See Figure 5.5). Removal efficiencies for c-DCE ranged from -147% to 22% while the apparent removal efficiencies for VC ranged from -97% to zero. Two sampling events showed production of c-DCE. Removal efficiencies of zero to 20% were identified during eleven sampling events and twice the removal efficiencies of c-DCE exceeded 20%. VC apparent removal efficiencies demonstrated accumulation during four sampling events while the remaining eleven events had no detectable VC.

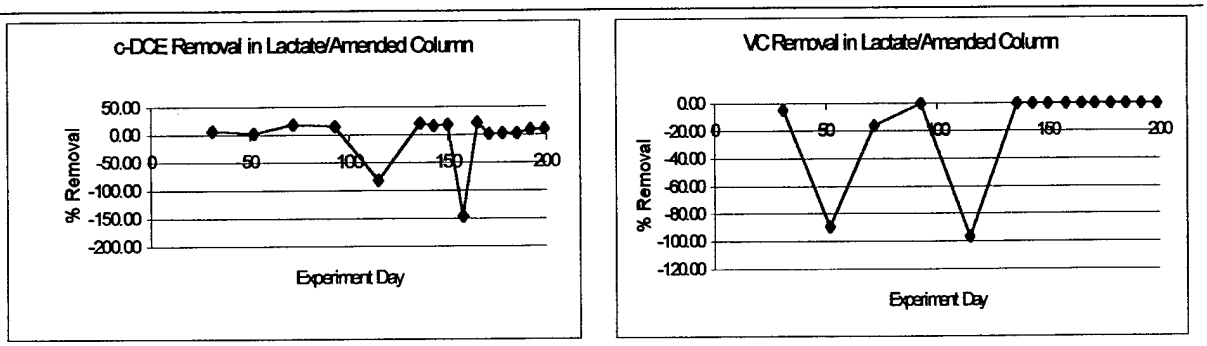

Figure 5.5. Chloroethene Removal Efficiencies in the Lactic Acid/Amended Column

Chloroethene Degradation in the Presence of Propionic Acid

Removal efficiencies of c-DCE and apparent removal efficiencies of VC in the propionic acid column ranged from -134% to 38% and -62% to zero respectively (See Figure 5.6). Removal efficiencies for c-DCE suggest the production of c-DCE only once (day 158) while

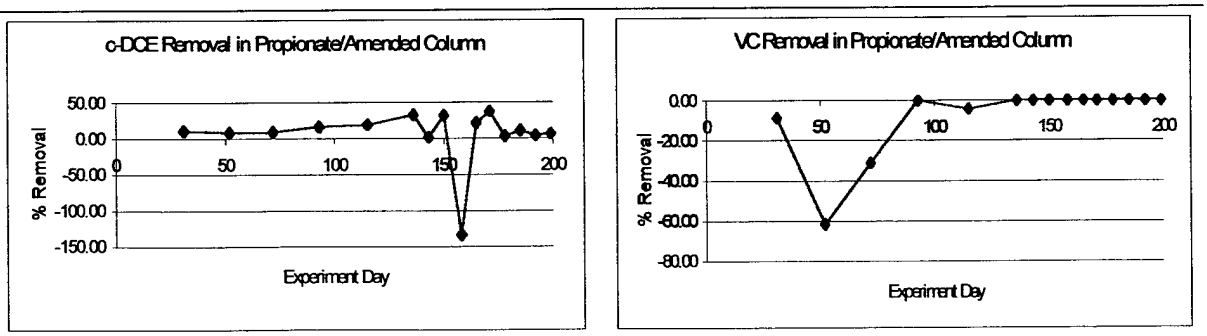

Figure 5.6. Chloroethene Removal Efficiencies in the Propionic Acid/Amended Column

removal efficiencies were between zero and 20% ten time and exceeded 20% four times. The apparent removal efficiencies of VC demonstrated the accumulation of VC during four sampling events while the remaining eleven events showed no detectable VC.

Chloroethene Degradation in the Presence of n-Propanol

In the column supplied with n-propanol, the removal efficiencies for c-DCE ranged from -93% to 28% while the apparent removal efficiencies for VC ranged from -37% to zero (See Figure 5.7). Removal efficiencies of c-DCE indicate the production of c-DCE only once (day 158) while 12 sampling events demonstrated removal efficiencies between zero and 20% and two sampling events demonstrated removal efficiencies exceeding 20%. The VC apparent removal efficiencies for the propanol column also demonstrated four events that show VC accumulation while the other eleven events showed no detectable VC.

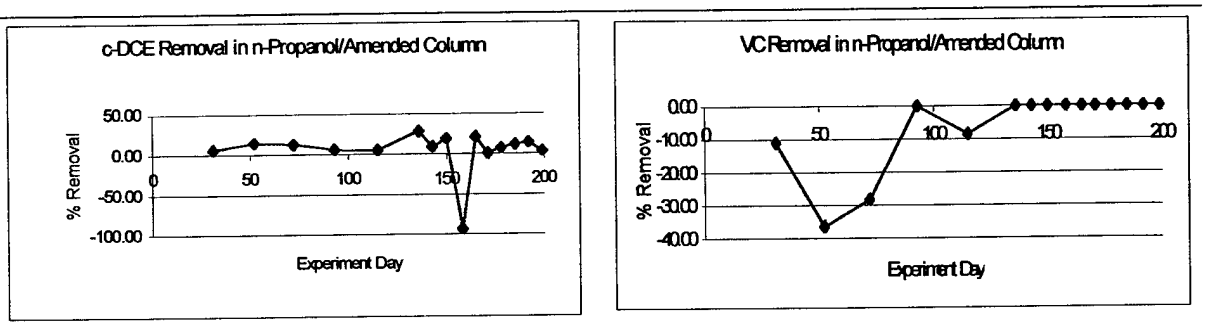

Figure 5.7. Chloroethene Removal Efficiencies in the n-Propanol/Amended Column

Chloroethene Degradation in the Presence of Toluene

Removal and apparent removal efficiencies in the toluene column ranged from -179% to 25% for c-DCE and -93% to zero for the VC (See Figure 5.8). Two sampling events demonstrated the apparent production of c-DCE while eleven sampling events demonstrated removal efficiencies between zero and 20% and two sampling events demonstrated removal

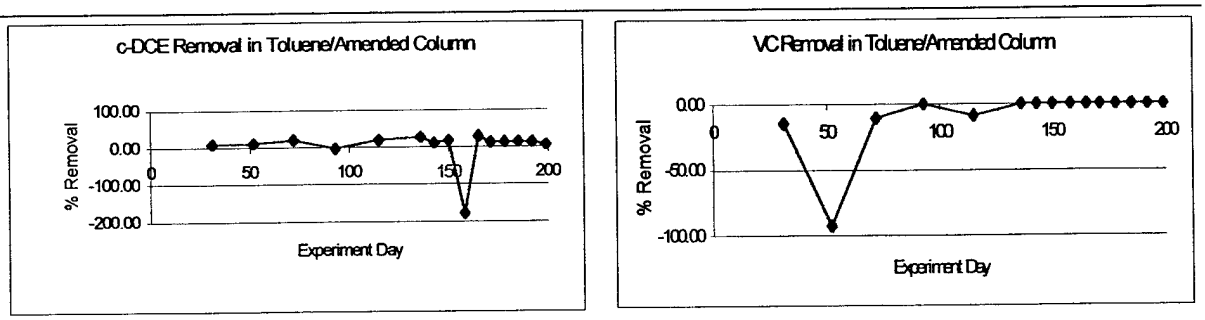

Figure 5.8. Chloroethene Removal Efficiencies in the Toluene/Amended Column

efficiencies greater than twenty percent. VC accumulation was demonstrated during four sampling events while the remaining eleven sampling events showed no detectable VC.

COMPARISON OF DECHLORINATION EFFICIENCIES

The wide range of dechlorination efficiencies and the lack of obvious trends make comparison of the various removal efficiencies difficult. However, to address the stated objectives, comparisons between unamended, amended, and electron donor supplied columns must be accomplished. The following paragraphs document these comparisons in an effort to identify the best conditions for in-situ reductive dehalogenation at OU-1.

Comparison of Background Columns; Unamended versus Amended

By comparing the unamended column with the vitamin and yeast-amended column removal efficiencies, we see that both columns have inconsistent efficiencies and show both the production or accumulation of c-DCE and high levels of c-DCE removal. The unamended column shows c-DCE production more frequently than the amended column, however, the amended column shows a much higher level of c-DCE production (day 158). The number of sampling events that demonstrate c-DCE removal in these columns is very similar, but the unamended column removal efficiencies tend to be larger in magnitude. Average removal efficiencies for the unamended and amended columns are 17% and 7% respectively. From the data available, the unamended column demonstrated greater c-DCE removal efficiencies than that of the vitamin and yeast-amended column. By comparing these two columns, there is no apparent advantage to adding vitamins and yeast to stimulate microbial growth, however, more consistent c-DCE removal efficiencies are needed to substantiate this conclusion.

The unamended and amended columns both demonstrate a VC accumulation phase that may represent biological acclimation. This is followed by a series of samples with no detectable VC. These data show that when c-DCE dechlorination is occurring in these columns, VC is also dechlorinated within the columns and VC accumulation does not persist. In each column there is only one event that clearly demonstrates actual VC removal. In the unamended column removal is shown at 8% in samples collected on day 31 while the amended column showed complete removal in the samples collected on day 158. Based on

the available apparent removal efficiencies, the performance of these columns is similar and there is no apparent advantage to supplying vitamins and yeast.

Comparison of Different Donor Dechlorination Efficiencies

In each column supplied vitamins, yeast, and an electron donor, removal efficiencies cover a wide range but all follow a similar pattern. In all columns some c-DCE production is demonstrated and all columns showed their highest production in the day 158 samples. The butyrate column had the highest frequency of c-DCE production with three sampling events showing production. The toluene column had the highest single-event c-DCE production represented by a removal efficiency of -179% (day 158 samples). During dechlorination, all columns showed similar removal efficiencies with the highest single-event removal efficiency of 38% demonstrated in the propionate column. Strongly influenced by the results of day 158, the average removal efficiencies for the columns supplied electron donors ranged from -5% to 7%. The n-butyric and lactic acid columns both had negative average removal values at -2% and -5% respectively. The benzoic acid column had the highest average removal of 7% followed closely by the propionic acid and n-propanol columns which both averaged 5% c-DCE removal. A comparison of the data suggests that of the electron donors examined, benzoic acid is the best source of electrons needed to support reduction of c-DCE. However, data from the propionic acid and n-propanol columns also suggest they supply adequate electrons to support sustained reduction of c-DCE. Further and more consistent removal data is needed before one preferred electron donor can be specified.

The pattern of apparent VC removal is very similar for all columns supplied electron donors. All columns began with low levels of VC accumulation (5-14%) followed by an increase in accumulation. This accumulation then dropped to undetectable levels of VC only to be followed by accumulation in all columns on day 115. After day 115 all columns showed zero apparent VC removal. The worst single VC accumulation event occurred in the lactic acid column (-97%) followed closely by the n-butyric acid column (-95%). Average apparent removal efficiencies showed n-propanol had the lowest VC accumulation (14%) during acclimation, however, benzoic and propionic acids supported only slightly higher VC accumulation during acclimation. Further data is needed to accurately define the electron donor that best supports VC removal.

By comparing the six columns that received electron donors it is difficult to select the single donor that best supported complete reductive dehalogenation of c-DCE. Benzoic acid had the highest average removal efficiency of c-DCE while n-propanol had the lowest accumulation for VC. Propionic acid had similar removal efficiencies to both benzoic acid and n- propanol for both these reductive steps while benzoic acid and n-propanol were similar to each other for both steps. The removal efficiencies for n-butyric and lactic acids indicated they would not be as efficient at supporting reductive dechlorination of c-DCE or VC. The removal efficiency of toluene placed it between these two groups with regard to supporting complete reductive dechlorination.

Comparison of Donor Column Dechlorination Efficiencies to Background Columns

A comparison of c-DCE removal efficiencies in columns provided an electron donor and the background columns suggests the electron donors did not offer an advantage to dechlorinators in this experiment. The vitamin and yeast amended column demonstrated the highest single-event removal at 69%, followed closely by the unamended column at 62%. These efficiencies were much higher than the highest event in the donor supplied columns which was 38%. Average removal efficiencies for all columns receiving the vitamin and yeast amendment were strongly affected by the high c-DCE production values noted on day 158. The amended column with no electron donor had the same average c-DCE removal efficiency as the benzoic acid supplied column while it had a better average removal than the other electron donor supplied columns. The average removal efficiency for the amended column was 7% while the electron donor supplied columns averaged 7% for benzoic acid, 5% for propionic acid and n-propanol, 0.6% for toluene, -2% for n-butyric acid, and -5% for lactic acid. In comparison, the unamended column with no donor supplied had an average removal efficiency of 17%. Based on the average removal efficiencies, neither the vitamins, yeast, nor electron donors appear to offer an advantage for accelerating reductive dechlorination under conditions present in this experiment. It must, however, be noted that, while all columns demonstrated a reduction of dissolved oxygen (DO) between the influent and effluent samples, the unamended column maintained higher DO levels. Effluent DO values for the unamended column ranged from 1 to 2 part per million (ppm) while the effluent from all amended columns was consistently below 0.5 ppm. This may have given an advantage to the oxidative dechlorination of c-DCE in the unamended column while the

amended columns did not have excess DO and were limited to the energetically more demanding reduction of c-DCE.

Apparent VC removal efficiencies suggest the unamended column acclimated more rapidly than the amended and donor supplied columns. The preponderance of nondetectable levels of VC make it difficult to conclude vitamin amendments or electron donors offer an advantage in avoiding the accumulation of VC during the dechlorination of c-DCE.

DISCUSSION OF DECHLORINATION EFFICIENCIES

During most sampling events the concentration of c-DCE appeared to be decreasing, however, the explanation for this decrease is not clear and may be attributed to a variety of processes. Typical c-DCE removal efficiencies throughout the experiment ranged from 2% to 30% and results from c-DCE samples do not indicate a microbial acclimation period occurred. Occasional unexplained negative removal efficiencies were noted. Of particular interest are the samples collected on day 158 that suggest high levels of c-DCE production, however, these results are suspected to be the product of poor sampling technique. With electron donors supplied well in excess of the calculated demand, results do not indicate a population of microbial dechlorinators able to utilize the donors and establish a robust population capable of degrading the c-DCE according to Monod kinetics. Degradation that did occur may be attributed to an existing population of dechlorinators that were not able to multiply significantly, cometabolism within the columns, or aerobic removal resulting from sample collection and handling.

Analytical results for VC offer a more promising outlook for dechlorinators. After an initial acclimation period (three months), nearly all sample results for VC were below detectable limits. Column influent samples showed less than detectable levels of VC, however, degradation of c-DCE should have lead to some production of VC within the columns. All production of VC within the columns was not detectable at the effluent of the columns in nearly all sampling events. Again, the overall database of results is not consistent enough to conclude this to be the results of dechlorinator activity, but VC results certainly suggest it.

A review of chloride levels was completed to evaluate the complete reduction of c-DCE. Due to financial constraints, only one set of chloride samples was analyzed. In all columns, except the unamended column, a slight increase in chloride concentration was observed.

Though initially encouraging, the levels of chloride production could easily be attributed to the chloride available from the vitamin amendments (See Appendix I for chloride calculations and results). With the vitamins serving as a possible source of chloride, it was not possible to demonstrate c-DCE reduction by examining chloride production.

Ethene and methane were also examined as indicators of dechlorination and results were inconsistent but showed a decrease in average ethene concentrations and an increase in average methane concentrations. Ethene results intermittently showed the production of ethene, possibly from the reduction of VC, in all columns except the unamended column. The average removal efficiencies in all these columns indicate a loss of ethene and may contraindicate reductive dechlorination. A review of ethane results indicates that rapid conversion of the produced ethene to ethane did not occur. Alternatively these results may also indicate complete mineralization of chloroethenes. The unamended column showed no ethene production while removal efficiencies were lower than in any of the donor supplied columns. The highest level of ethene removal was seen in the column supplied propionic acid while the worst removal was in the column supplied only vitamins and yeast. All columns showed periodic methane removal, however, average removal efficiencies for all columns indicate methanogenic conditions. Energetics suggest this indicates the depletion of available electron acceptors including oxygen, nitrate, chloroethenes, and sulfate, however, in this experiment c-DCE clearly persisted while methane was produced. This production of methane demonstrated the competition for reducing equivalents between dechlorinators and methanogenic microorganisms. Methane production was lowest (45%) in the unamended column and of the donor supplied columns methane production was lowest (74%) in the propionic acid column while it was highest (-232%) in the column supplied with lactic acid. The remaining columns showed methane production ranging from 99% to 125%.

PREDICTION OF FIELD DECHLORINATION VALUES

Having established experimental conditions similar to those within OU-1, predictions can be made regarding the level of dechlorination per distance the groundwater travels. The unamended column demonstrated the highest c-DCE removal efficiencies and provides the best basis for predictions within OU-1, assuming enhanced dechlorination is not attempted. Experimental results show that the highest influent c-DCE concentration also has the highest removal per distance traveled though the aquifer solids. At a groundwater concentrations of

2736 µg/L experimental conditions demonstrated 7.33 µg/L of c-DCE was lost per cm of aquifer solids traversed. The average c-DCE removal per cm of aquifer solids used throughout this experiment was calculated to be 1.33 µg/L/cm of aquifer solids and reflects the predicted removal for current conditions within OU-1 (See Appendix H). A predicted loss of 1.33 µg/L/cm assumes the same in situ removal efficiencies as those seen in the laboratory and is likely an optimistic prediction, however, this level of removal has been demonstrated and could be used in future decisions regarding clean up proposals for OU-1.

OTHER REACTIONS OF INTEREST

The complete reduction of c-DCE without the accumulation of VC was the primary focus of this experiment, however, a review of analytical data shows some other beneficial reactions consistently occurred. Though changes in groundwater may have had an influence on chemical concentrations, analytical results indicated decreasing concentrations of 1,1,1-trichloroethane (1,1,1 TCA), 1,4-dichlorobenzene (1,4 DCB), and chlorobenzene (CB) as water passed through the columns. For all these compounds the last three sampling events suggest a change in trends, however, not enough data are available to pursue this change.

Nearly complete removal of 1,1,1 TCA was observed in all amended columns. The unamended column showed varying degrees of 1,1,1 TCA production and removal and had an average removal of 28%. In contrast, all columns that received the vitamin and yeast amendment had typical removal values of 100% with average removal efficiencies ranging from 71% to 80% in spite of three sampling events with no influent 1,1,1 TCA and therefore assigned apparent removal efficiencies of zero.

Chlorobenzene and 1,4 DCB had between 25% and 39% average removal efficiencies in all amended columns. CB results showed limited periods of production in all vitamin and yeast amended columns, however, removal efficiencies were consistent during periods of removal. All amended columns showed CB removal approximating twice that of the unamended column. The 1,4 DCB results showed a pattern similar to the removal of VC. After an initial period of 1,4 DCB accumulation (three months), removal efficiencies became consistent between 30% and 60%. The average removal efficiency for each of the amended columns was more than an order of magnitude greater than the average removal efficiency in the unamended column.

CHAPTER VI
CONCLUSIONS

After a review of all data and procedures associated with this research project, conclusions have been drawn to support the stated objectives as well as address issues associated with future work similar to this effort. The high degree of variability in analytical results makes conclusions regarding reductive dechlorination difficult, however there are sufficient data regarding removal efficiencies to address some of the objectives. Though it cannot be conclusively stated that the physical setup or operations of this project contributed to incomplete dechlorination, some operational limitations are clear.

CONCLUSIONS DIRECTLY RELATED TO STUDY OBJECTIVES

Degradation of c-DCE did occur without the accumulation of VC in unamended, amended, and donor supplied columns. The removal of c-DCE was initially demonstrated in the first sample set collected on day 31. The VC removal demonstrated an acclimation phase which was followed by compete removal of VC regardless of the c-DCE concentration or c-DCE removal efficiencies during the same sampling event.

Of the electron donors supplied, benzoic acid supported the highest c-DCE removal. Propionic acid and n-propanol had similar c-DCE removal efficiencies while n-butyric and lactic acid had the lowest c-DCE removal efficiencies. In all cases the data are not consistent enough to predict success or failure if applied in-situ.

The addition of vitamins and yeast did not improve reductive dechlorination of c-DCE or VC. For the c-DCE to VC step, the unamended column had better removal efficiencies than any column receiving vitamins and yeast. Similarly for the VC-ETH step, the unamended column more rapidly acclimated and demonstrated complete removal of VC faster than any column receiving vitamins and yeast. These data showed that the microorganisms involved in these two steps are not nutrient limited and vitamin amendments are not necessary for reductive dechlorination to proceed.

This experiment has failed to demonstrate a cost-effective treatment alternative to the currently proposed pump-and-treat system intended for use at OU-1. Regardless of the abundance of indicators suggesting the application of an electron donor to stimulate the

reductive dechlorination of c-DCE in OU-1, results from this experiment do not offer conclusive evidence that in-situ reductive dechlorination can be enhanced and field testing should not be attempted at this time. Experimental results under different operating conditions could prove more successful and ultimately offer a treatment solution.

SUPPLEMENTAL STUDY CONCLUSIONS

Based on removal efficiencies, the column that showed the best reduction of c-DCE was the unamended column. Though oxygen levels of 1-2 ppm may have facilitated the higher removal values, this can not be concretely determined.

An inadequate number of analytical parameters were regularly examined. The analysis of chloride, dissolved hydrogen and other electron acceptors including nitrate, manganese (IV), iron (III), and sulfate are needed to determine the removal pathways and establish a balance for the reducing equivalents.

The c-DCE lower threshold concentration for the microorganisms in this soil and groundwater is not known, therefore we do not know if experimental c-DCE concentrations ever exceeded this threshold. Past research has typically shown 100 to 300 μM (9,694-29,082 ppb), and in some cases 10 μM (969 ppb) (Yang and McCarty, 1998 and Beeman *et al*, 1994) to be above threshold limits. The highest concentration of c-DCE recorded during this experiment was 2,736 ppb while typical concentrations were less than 300 ppb. Even after the c-DCE available in the groundwater decreased to negligible levels, the attempted spiking failed to raise the delivered concentrations of c-DCE to 1,000 ppb. As a results typical OU-1 site levels were not demonstrated to be above the lower threshold concentration for indigenous microorganisms.

The acclimation period of indigenous c-DCE dechlorinating microorganisms is not known and therefore we do not know if experimental conditions allowed acclimation to occur. Site characteristics indicate that dechlorinators are present in-situ, however once soils and groundwater are taken from the site, the delicate conditions necessary to support these microorganisms are altered. Even though great effort was extended to keep the soils and groundwater as close to in-situ conditions as possible, variations did occur. Column operating temperatures for this experiment were 19°C which is much higher than in-situ conditions. During water collection, sampling, and transferring to the feed assemble the

water was mixed causing the system to function as a series of microaerobic columns (< 2.0 ppm oxygen with oxygen utilizing microbial activity) instead of anaerobic (zero oxygen and no oxygen utilizing microbial activity) columns. The addition of amendments alters the water chemistry and may offer advantages to microorganisms other than dechlorinators.

The addition of vitamin and yeast facilitated the removal of 1,1,1 TCA, 1,4 DCB and CB. In all columns receiving the amendments, the removal of these compounds was substantially greater than that seen in the unamended column. In direct conflict with the reduction of chloroethenes, these data show nutrient limitations for the organisms facilitating these reductions.

Samples collected from all vitamin and yeast amended columns on day 158 demonstrated results far removed from the predominant values in all amended columns. These results demonstrated a high level of c-DCE production or accumulation and affected much lower average removal efficiencies for all these columns. To further address the effect of this sampling event, removal rates based on time between sampling events and average removal rates excluding this sample were calculated and can be found in Appendix H. These sample results did not, however, affect the comparative relationships between column performance and the same conclusions still apply.

The effects of running microaerobic microcosms as opposed to anaerobic microcosms are not known. A majority of the literature reviewed addressed similar studies as anaerobic, however, very few offered any data regarding oxygen content. This research demonstrated the difficulty in maintaining anaerobic conditions and showed the greatest dechlorination in the column with the highest oxygen content.

CHAPTER VII
RECOMMENDATIONS

The construction and operation of this system, as well as the review of analytical results, illuminated some problem areas encountered during this experiment and promoted the generation of recommendations to improve further research. Clearly the demonstrated results do not show complete manifestation of the theories given in Chapter IV, however, further research exploring different operating parameters should be conducted before enhanced in-situ biological treatment is eliminated as a treatment technology for OU-1.

Benzoic acid, propionic acid, and n-propanol should be included in future studies. These compounds were the top performers in this study and may demonstrate greater success in future studies incorporating recommendations listed below.

The delivered concentration of c-DCE should be better regulated to provide microbial populations a stable supply of electron acceptors on which to acclimate and grow. The varied concentration of c-DCE may have made it difficult for a microbial population to grow to a level sufficient to utilize and reduce the contaminants to below the MCL of 70 ppb. Stabilizing concentrations may allow the microbes to acclimate, grow and utilize the c-DCE in a manner that demonstrates Monod kinetics. Sufficient groundwater needed for the duration of any future research should be collected and spiked as a single batch. Continued mixing should ensure consistent concentrations throughout the project.

Concentrations of 1,000 ppb and higher should be evaluated to identify the c-DCE threshold concentrations associated with OU-1 indigenous microorganisms. The spiking goal of 1,000 ppb (10.3μM) was established based on average groundwater monitoring data near the Chemical Disposal Pits. Past research (Yang and McCarty, 1998 and Beeman *et al*, 1994) has shown this level to be above threshold concentration for various microbial populations, however the population in OU-1 may be quite different than populations in other research. Spiking never achieved the goal of 1,000 ppb; therefore it was never determined that this level is above threshold concentrations for OU-1. The identification of the threshold concentration for microorganisms in OU-1 is critical for site treatment applications. If the lower threshold concentration exceeds the clean-up goal, in this case an MCL of 70 ppb, the technology is not appropriate for the site.

Nutrient limitations should be further explored, however the vitamin recipe used in this research should be simplified. The most recent draft of the RABITT protocol (Morse *et al*, 1998) suggests the use of only vitamin B_{12}. The vitamin recipe used in this experiment was followed faithfully, yet the mixing of these vitamins adds one more opportunity for slight variation and operator error.

Further evaluations attempting to mimic site conditions should operate at lower temperature. The dominant theory is that elevating the temperature will increase microbial growth and the probability of successfully promoting dechlorinator growth, however this theory has not always proved correct. To truly mimic OU-1 conditions, columns should be operated at 10°C (Montgomery Watson 1995).

Routine analysis of chemical parameters should be expanded in any future study to identify appropriate electron donors for OU-1. Chloride, dissolved hydrogen, and additional electron acceptors should be included in the list of analytes. Reductive dechlorination of chloroethenes results in an increase in the concentration of chloride ions and analytical results could provide conclusive evidence that this process is occurring. Chloride ion results would also provide the missing data needed to calculate a mass balance on the chlorine within the system. Each terminal electron accepting process has a characteristic hydrogen concentration associated with it and analytical data could be used to indicate the dominant redox processes. Analysis of nitrate, manganese (IV), iron (III) and sulfate, at least initially, could provide evidence of the depletion of other electron acceptors. Failure to demonstrate depletion of these competing electron acceptors, particularly the nitrate, could indicate the microbial population is unable to utilize the chloroethenes as electron acceptors.

Future column studies should include a longer experimental run time. The RABITT protocol (Morse *et al*, 1998) indicates studies should include a minimum of six months. It is likely that indigenous microbial populations would not require this long to reacclimate to soils and water in the assembled columns, however, this can not be concretely demonstrated. The time needed to deplete other available electron acceptor, acclimatize a healthy population of dechlorinators, and allow the dechlorination process to proceed is influenced by site conditions and may be greater than the 199 days allowed in this experiment.

A microbial examination using most probable number (MPN) assays should be considered. Of interest would be anaerobic heterotrophs, sulfate reducers, hydrogen and

acetate using methanogens and dechlorinators. Procedures for these MPN assays are described by Maymo-Gatell *et al.* (1995). Results of these tests could be compared to chemical measurements from the study and provide some indication of the types of microorganisms indigenous to these soils and water.

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Appendices

Appendix A

Soil Respirometry Test Procedure
OU-1 Electron Donor Study

Equipment:

12	250mL E-flasks
24	glass tubes
12	2 hole stoppers
12	glass tube septum
12	manometer hoses
1	ruler
12	syringes (5mL w/21 guage needles)
300g	Silica sand
1200g	OU-1 Soil
1	Sterile Filter Apparatus
2 ea	filters (sequential down to 0.2um)
1	Balance

Tests:

3	Soil, Amended Water, + Acetate
3	Soil, Amended Water, + Propanol
2	Sand, + D.W. (Thermal Barometer)
2	Soil, Amended Water, Acetate, + Sodium Azide
2	Soil, Amended Water, Propanol, + Sodium Azide

Concentrations:
Acetate = TBD based on solubility
Propanol = 5.22mL/L

Procedure:

- Add 150 g aquifer soils to two 250 mL flasks, cover with aluminum foil and autoclave for 30 minutes
- Autoclave glassware, hoses, stoppers, filters for 30 minutes
- Filter the acetate or propanol amended groundwater to sterilize
- Filter the acetate or propanol amended groundwater and sodium azide to sterilize
- Prep the anaerobic glovebox
  - Place all items in the glovebox and seal
  - Fill and purge the glovebox with nitrogen gas twice
  - Fill the glove box with 95% nitrogen/5% hydrogen
  - Turn on oxygen scavengers in the glovebox
- In an anaerobic glovebox prepare test microcosms, See Figure 1
  - Allow soils to drain excess water onto sterilized worksurface
  - Place 150 g of OU-1 soil in the flask
  - Add 30 mL (or enough to fill soil pore space, 60 mL for the distilled water flasks) of the filtered water containing acetate or propanol to the appropriate flasks
  - Add 30 mL (or enough to fill soil pore space) of the filtered water containing acetate or propanol and sodium azide to the appropriate flasks
- Leave all microcosms covered with aluminum foil in the anaerobic glovebox for five days to acclimate
- After the acclimation period, while still in the anaerobic glove box, stopper the microcosms and add the sampling glass tube and the manometer tubing assembly
- Remove the microcosms from the anaerobic glovebox and secure the stopper and manometer lines to minimize air transfer and facilitate pressure readings, add 5mL salt water (<75% solubility limit of sodium chloride) to the manometer lines to make reading possible, See Figure 2
- Seal the stoppers into the flasks using copper wire
- Collect gas samples from each flask using the syringe, analyze using GC/TCD for CO_2 and CH_4
- Take manometer readings every 4 hours for 48 hours or as needed based on preliminary observations
- At the end of 48 hours, collect gas samples from the sampling tube and analyze using GC/TCD for CO_2 and CH_4

Figure 1

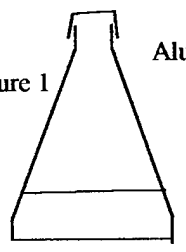
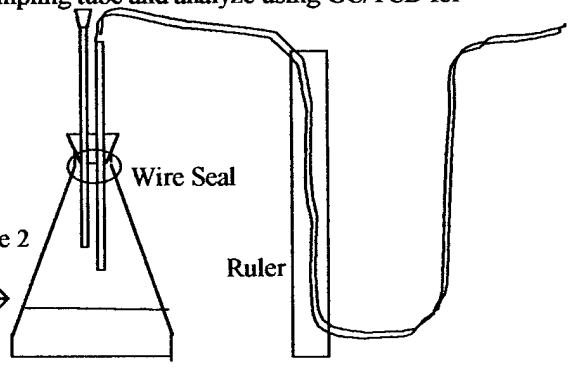


Figure 2



Appendix A
Soil Respirometry Results

Soil Test Measurements 23 Nov 98

	Carbon Dioxide			Oxygen			Methane		
	Peak Area t=0.95	Calculated % Concentration	Calculated ppm	Peak Area t=1.86	Calculated % Concentration	Calculated ppm	Peak Area t=4.95	Calculated % Concentration	Calculated ppm
DW1	0	-0.36	-3581.44	8800598	3.40	34002.99	0	0.08	798.08
DW2	0	-0.36	-3581.44	5324939	1.66	16624.70	0	0.08	798.08
SWP1		-0.36	-3581.44	5912176	1.96	19560.88	0	0.08	798.08
SWP2		-0.36	-3581.44	4519845	1.26	12599.23	0	0.08	798.08
SWP3		-0.36	-3581.44	5356726	1.68	16783.63	0	0.08	798.08
SWP NaAZ1		-0.36	-3581.44	6179004	2.09	20895.02	0	0.08	798.08
SWP NaAZ2		-0.36	-3581.44	6200210	2.10	21001.05	0	0.08	798.08
SWA1	2690450	0.99	9870.82	4725622	1.36	13628.11	0	0.08	798.08
SWA2	3199318	1.24	12415.16	6704892	2.35	23524.46	0	0.08	798.08
SWA3	2600449	0.94	9420.81	6268868	2.13	21344.34	0	0.08	798.08
SWA NaAZ1	1893040	0.59	5883.77	7650078	2.83	28250.39	0	0.08	798.08
SWA NaAZ2	1878442	0.58	5810.78	5188371	1.59	15941.86	0	0.08	798.08

Soil Test Measurements 25 Nov 98

	Carbon Dioxide			Oxygen			Methane		
	Peak Area t=0.95	Calculated % Concentration	Calculated ppm	Peak Area t=1.86	Calculated % Concentration	Calculated ppm	Peak Area t=4.95	Calculated % Concentration	Calculated ppm
DW1	1913724	0.66	6589.89	14096789	6.66	66644.13	66874	0.03	336.96
DW2	0	-0.30	-2978.73	11773353	5.50	55026.95	0	0.02	169.77
SWP1		-0.30	-2978.73	15348802	7.29	72904.20	3037	0.02	177.37
SWP2		-0.30	-2978.73	7624430	3.43	34282.34		0.02	169.77
SWP3		-0.30	-2978.73	9651589	4.44	44418.13	13651	0.02	203.90
SWP NaAZ1		-0.30	-2978.73	15147621	7.19	71898.29		0.02	169.77
SWP NaAZ2		-0.30	-2978.73	7330272	3.28	32811.55		0.02	169.77
SWA1	4458044	1.93	19311.49	6249406	2.74	27407.22		0.02	169.77
SWA2	4608720	2.01	20064.87	6475097	2.85	28535.67		0.02	169.77
SWA3	3786258	1.60	15952.56	11492262	5.36	53621.50		0.02	169.77
SWA NaAZ1	3396582	1.40	14004.18	12198472	5.72	57152.55		0.02	169.77
SWA NaAZ2	2990252	1.20	11972.53	5231980	2.23	22320.09		0.02	169.77

Soil Test Measurements 30 Nov 98

	Carbon Dioxide			Oxygen			Methane		
	Peak Area t=0.95	Calculated % Concentration	Calculated ppm	Peak Area t=1.86	Calculated % Concentration	Calculated ppm	Peak Area t=4.95	Calculated % Concentration	Calculated ppm
DW1	1632316	0.65	6501.87	9530478	9.01	90120.32	32878	0.08	770.54
DW2	1369356	0.52	5187.07	14266925	13.75	137484.79	0	0.07	688.35
SWP1	4920965	2.29	22945.12	12341292	11.82	118228.46	19074	0.07	736.03
SWP2	2495829	1.08	10819.44	931625	0.41	4131.79	56845	0.08	830.46
SWP3	3720578	1.69	16943.18	6753294	6.23	62348.48	35701	0.08	777.60
SWP NaAZ1	2566296	1.12	11171.77	2858820	2.34	23403.74		0.07	688.35
SWP NaAZ2	3188980	1.43	14285.19	1157333	0.64	6388.87		0.07	688.35
SWA1	5750165	2.71	27091.12	5391212	4.87	48727.66		0.07	688.35
SWA2	6386175	3.03	30271.17	5667144	5.15	51486.98		0.07	688.35
SWA3	6120172	2.89	28941.15	10239988	9.72	97215.42		0.07	688.35
SWA NaAZ1	5582297	2.63	26251.78	10147776	9.63	96293.30		0.07	688.35
SWA NaAZ2	4517312	2.09	20926.85	3917041	3.40	33985.95		0.07	688.35

t = sample run time to representative peak
DW = Sand and Distilled Water
SWP = Soil, Amended Water, and n-Propanol
SWPNaAZ = Soil, Amended Water, n-Propanol, and Sodium Azide
SWA = Soil, Amended Water, and Acetate
SWANaAZ = Soil, Amended Water, Acetate, and Sodium Azide

Appendix A
Soil Respirometry Results

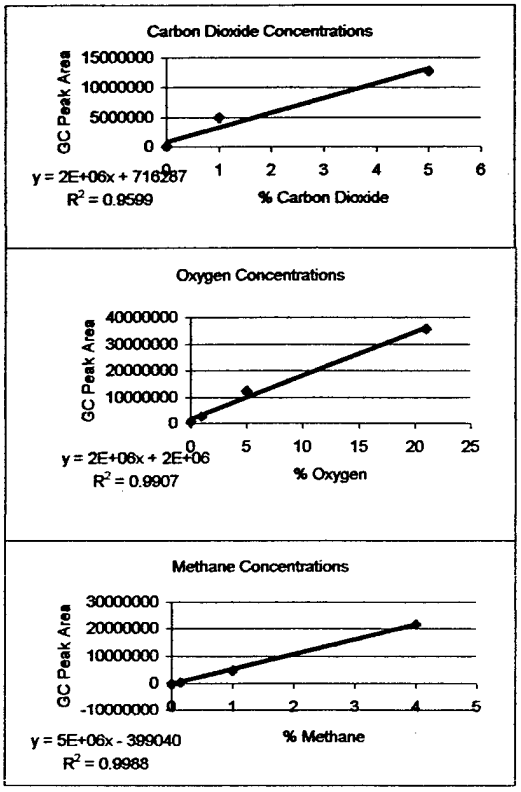
Comparison of Values Table

Day		DW1	DW2	SWP1	SWP2	SWP3	SWP NaAZ1	SWP NaAZ2	SWA1	SWA2	SWA3	SWA NaAZ1	SWA NaAZ2
All Values in ppm													
Carbon Dioxide													
1	23-Nov	-3581	-3581	-3581	-3581	-3581	-3581	-3581	9871	12415	9421	5884	5811
3	25-Nov	6590	-2979	-2979	-2979	-2979	-2979	-2979	19311	20065	15953	14004	11973
8	30-Nov	6502	5187	22945	10819	16943	11172	14285	27091	30271	28941	26252	20927
Oxygen													
1	23-Nov	34003	16625	19561	12599	16784	20895	21001	13628	23524	21344	28250	15942
3	25-Nov	66644	55027	72904	34282	44418	71898	32812	27407	28536	53621	57153	22320
8	30-Nov	90120	137485	118228	4132	62348	23404	6389	48728	51487	97215	96293	33986
Methane													
1	23-Nov	798	798	798	798	798	798	798	798	798	798	798	798
3	25-Nov	337	170	177	170	204	170	170	170	170	170	170	170
8	30-Nov	771	688	736	830	778	688	688	688	688	688	688	688

Appendix A
Soil Respirometry Results

Soil Test Calibration Measurements 23 Nov 98

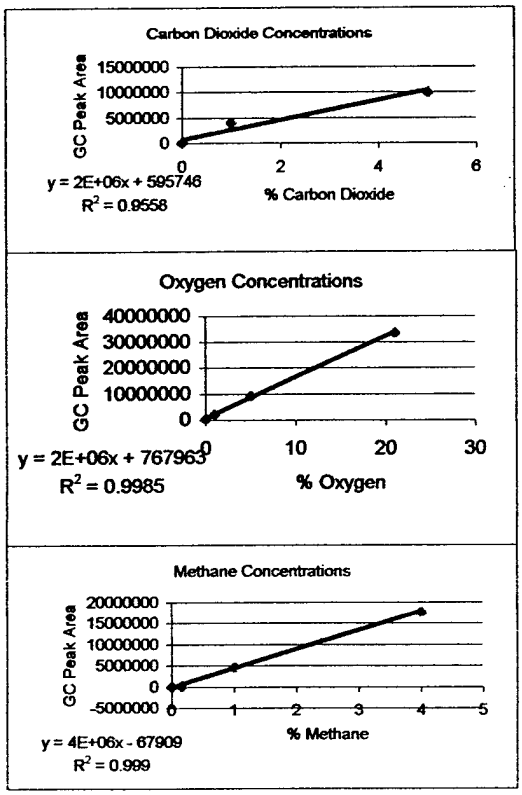
Carbon Dioxide		Oxygen		Methane	
%Concentration	Peak Area t=0.95	%Concentration	Peak Area t=1.86	%Concentration	Peak Area t=4.95
0	0	21	35696296	0	0
0	0	0	534078	0.15	347598
1	4986511	1	2655040	1	4631097
5	12755675	5	12183233	4	21584422



Appendix A
Soil Respirometry Results

Soil Test Calibration Measurements 25 Nov 98

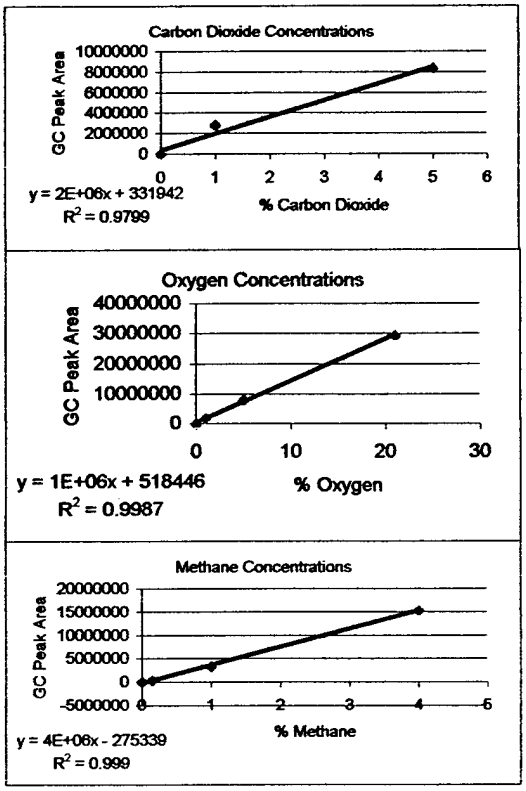
Carbon Dioxide		Oxygen		Methane	
%Concentration	Peak Area t=0.95	%Concentration	Peak Area t=1.86	%Concentration	Peak Area t=4.95
0	0	21	33549276	0	0
0	0	0	123840	0.15	291596
1	4043697	1	2382692	1	4726118
5	10090805	5	9407890	4	17797927



Appendix A
Soil Respirometry Results

Soil Test Calibration Measurements 30 Nov 98

Carbon Dioxide		Oxygen		Methane		
%Concentration	Peak Area t=0.95	%Concentration	Peak Area t=1.86	%Concentration	Peak Area t=4.95	
0	0	21	29426138	0	0	Air
0	0	0	105431	0.15	233719	
1	2798875	1	1782991	1	3311818	
5	8351363	5	8130638	4	15251612	



Appendix B
Electron Donor Equations and Hydrogen Release Calculations

Selected Donors — H eqs

Butyric Acid (Butyrate) $CH_3CH_2CH_2COO^- + 7H_20 \rightarrow 3CO_2 + HCO_3^- + 20H^+ + 20e^-$

M.W. 88.12

(slow) fatty acid

$CH_3CH_2CH_2COOH+2H_2O \rightarrow 2CH_3COOH+2H_2$ — 2 H_2/mole / 20 ee/mole — **0.100 H_2/ee**

Benzoic Acid (Benzonate) $C_6H_5COO^- + 13H_2O \rightarrow 6CO_2 + HCO_3^- + 30H^+ + 30e^-$

M.W. 122.12 aromatic acid

$C_6H_5COOH+6H_2O \rightarrow 3CH_3COOH + 3H_2 + CO_2$ — 3 H_2/mole / 30 ee/mole — **0.100 H_2/ee**

Lactic Acid (Lactate) $CH_3CHOHCOO^- + 4H_20 \rightarrow 2CO_2 + HCO_3^- + 12H^+ + 12e^-$

M.W. 90.08 fatty acid

(fast) $CH_3CHOHCOOH + H_2 \rightarrow CH_3CH_2COOH$

(slow) $CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + 3H_2$

$CH_3CHOHCOOH + 2H_2O \rightarrow 2H_2 + CH_3COOH$ — 2 H_2/mole / 12 ee/mole — total release **0.167 H_2/ee**; slow release **0.111 H_2/ee**

Propionic Acid (Propionate) $CH_3CH_2COO^- + 5H_2O \rightarrow 2CO_2 + HCO_3^- + 14H^+ + 14e^-$

M.W. 74.08 fatty acid

(slow) $CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + 3H_2$ — 3 H_2/mole / 14 ee/mole — **0.214 H_2/ee**

n-Propanol $CH_3CH_2CH_2OH + 5H_2O \rightarrow 3CO_2 + 18H^+ + 18e^-$

M.W. 60.09

(fast) $CH_3CH_2CH_2OH + H_2O \rightarrow CH_3CH_2COOH + 2H_2$

(slow) $CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + 3H_2$

$CH_3CH_2CH_2OH + 3H_2O \rightarrow CH_3COOH + 5H_2$ — 5 H_2/mole / 18 ee/mole — total release **0.278 H_2/ee**; slow release **0.167 H_2/ee**

Toluene $C_7H_8 + 14H_2O \rightarrow 7CO_2 + 36H^+ + 36e^-$

M.W.92.13

(fast) $C_7H_8 + 2H_2O \rightarrow C_6H_5COOH + 3H_2$

(slow) $C_6H_5COOH+6H_2O \rightarrow 3CH_3COOH + 3H_2 + CO_2$

$C_7H_8 + 8H_2O \rightarrow 3CH_3COOH + 6H_2 + CO_2$ — 6 H_2/mole / 36 ee/mole — total release **0.167 H_2/ee**; slow release **0.083 H_2/ee**

Acetate (Soil Test) $CO_2 + HCO_3^- + 8H^+ + 12e^- \rightarrow CH_3COO^- + 3H_2O$

M.W.60.05

$CH_3COO^- + H \rightarrow CH_4 + CO_2$ — 1 H_2/mole / 8 ee/mole — total release **0.125 H_2/ee**

Appendix C
Electron Donor Delivery Calculations

Molar Concentrations of Donors Based on H_2 Demand and slow H_2 fermentation values
Worst Case Contaminat Concentrations from Remedial Investigation Report (Montgomery-Watson, 1995)
Demand = ((mol H_2demand/l)/mol H_2 donor/ee)* 1mol donor/ee

4.06E-03

Donor Concentration = X : Donor Flow Rate (X) = Total Flow (Conc Needed)

	mol H_2/l Demand	mol H_2/ee Donor	ee/1mol Donor	(mol/l) donor Needed	(mg/l) donor mol/l*mg/mol	Donor Bottle Concentration (mol/L)	(mg/L) *ml*	Total Donor Needed (mg)	Total Donor Needed (ml) mg/(SG*1000)
n-Butyric Acid (Butyrate)	4.06E-03	0.100	20	2.030E-03	178.88	1.051E-01	9261.292	13141.773	13.6325
S.G. : 0.964							*9.6071*		
Benzoic Acid (Benzonate)	4.06E-03	0.100	30	1.353E-03	165.27	7.007E-02	8556.430	12141.575	9.5905
S.G. : 1.266							*6.7586*		
Benzoate calculations due to solubility limits of crystal benzoic acid. Donor 1/4 as concentrated and supplied at 4 times the normal donor feed rate									
Benzoic Acid (Benzonate)	4.06E-03	0.100	30	1.353E-03	165.27	1.853E-02	2263.059	3211.281	2.5366
							1.7876		
Lactic Acid (Lactate)	4.06E-03	0.167	12	2.026E-03	182.50	1.049E-01	9448.388	13407.263	10.7258
S.G. : 1.250							*7.5587*		
Propionic Acid (Propionate)	4.06E-03	0.214	14	1.355E-03	100.39	7.016E-02	5197.401	7375.112	7.4271
S.G. : 0.993							*5.2340*		
n-propanol	4.06E-03	0.167	18	1.351E-03	81.16	6.993E-02	4201.848	5962.422	7.4067
S.G. : 0.805							*5.2197*		
Toluene	4.06E-03	0.083	36	1.359E-03	125.18	7.035E-02	6481.083	9196.656	10.6074
S.G. : 0.867							*7.4753*		
Solubility limits of toluene = 0.577ml/L. Donor at saturation limit is supplied at 4 times the normal donor feed rate but still 4X<demand									
4X Feed Rate	4.06E-03	0.083	36	1.359E-03	125.18	1.861E-02	1714.158	2432.390	2.8055
							1.9771		
Actual Toluene		0.083	36				499.9989		
	0.001184	Best Possible Delivery					*0.5767*		
Acetate	4.06E-03	0.083	8	6.114E-03	367.17	3.166E-01	19009.558		
(Soil Testing) S.G. : 1.048							*18.1389*		

Predicted Volume of Donor Needed:
Donor Solution Rate ml/min * 10080 min/wk * 32 wk/exp = 1419.26 ml/exp
1.42 L/exp

Predicted Total Fluid:
Total Solution Rate ml/min * 10080 min/wk * 32 wk/exp = 73479.17 ml/exp

73.48 L/exp	Per Column
587.83 L/exp	Total Experiment

X 8 Columns

Vitamins:
For Vitamin Demand (mg/L):

				Needed (mg)	(g/exp)
10		587.832		5878.32	5.88
20		587.832		11756.64	11.76
50		587.832		29391.6	29.39
100		587.832		58783.2	58.78

Resazurin	1		587.832		587.832	0.59
Yeast	20		587.832		11756.64	11.76

Appendix D
Hydrogen Demand Calculations

Concentrations from OU-1 Comprehensive RI Report Section 8

DCE Groundwater – up to 42,000 ug/L -Total DCE
DCE Soil – up to 4.2 mg/kg -Total DCE

Worst Case Well Data

Contaminant	Molecular Weight	Conc (ug/L)	Molar Conc (mol/L)	H equivalents	e equiv	eq H Demand mol H_2/liter	ee/liter
PCE	165.82	58	3.50E-07	4	8	1.40E-06	2.80E-06
TCE	131.38	2300	1.75E-05	3	6	5.25E-05	1.05E-04
DCE	96.94	42,000	4.33E-04	2	4	8.67E-04	1.73E-03
VC	62.5	2400	3.84E-05	1	2	3.84E-05	7.68E-05
						9.59E-04	1.92E-03
TCA	133.4	2000	1.50E-05	3	6	4.50E-05	9.00E-05
DCA	98.96	520	5.25E-06	2	4	1.05E-05	2.10E-05

Iron
Chlorinated Benzenes
etc

	1.01E-03	2.03E-03
Multiply by Safety Factor	4	4
Equivalent Hydrogen Demand	4.06E-03	
Equivalent Electron Demand		8.11E-03

Flow Rates

Feed Solution:	0.2234 ml/min
Donor Solution:	0.0044 ml/min
Total Feed Rate:	0.2278 ml/min

$$\frac{\text{mol } H_2\text{/liter demand}}{\text{mol } H_2\text{/ee donor}} \quad \frac{X\ 1\text{mol}}{\text{ee/mol donor}}$$

Appendix E
Electron Donor Properties and Actual Delivery Calculations

Measured TOC Levels Based on Equivalent Hydrogen Demand Calculations

	Butyrate	Benzoate	Lactate	Propionate	Propanol	Toluene
TOC (mg/L)	9261.29	8556.43	9448.39	5197.40	4201.85	6481.08
M.W.	88.12	122.12	90.08	74.08	60.09	92.13
Carbon Weight	48.00	84.00	36.00	36.00	36.00	84.00
Equivalent Carbon	0.54	0.69	0.40	0.49	0.60	0.91
As Carbon (mg/L)	5044.73	5885.52	3776.00	2525.73	2517.33	5909.16
As Carbon Based on Solubility (mg/L)		1556.60				455.88
Analytically Measured TOC						
25-Nov-98						
TOC (mg/L)	3400.00	1100.00	2600.00	2500.00	1800.00	2.30
% Recovery						
Based on Predicted Loading	67.40	18.69	68.86	98.98	71.50	0.04
Based on Solubility Limits		70.67				0.50
Equivalent Donor Supplied (mg/L)	6241.83	1599.19	6505.78	5144.44	3004.50	2.52
% of Predicted Actually Supplied	67.40	18.69	68.86	98.98	71.50	0.04
2-Feb-99						
TOC (mg/L)	5900.00	1900.00	3700.00	3000.00	2600.00	130.00
% Recovery						
Based on Predicted Loading	116.95	32.28	97.99	118.78	103.28	2.20
Based on Solubility Limits		122.06				28.52
Equivalent Donor Supplied (mg/L)	10831.42	2762.24	9258.22	6173.33	4339.83	142.58
% of Predicted Actually Supplied	116.95	32.28	97.99	118.78	103.28	2.20
Average Equivalent Donor Supplied	8536.63	2180.71	7882.00	5658.89	3672.17	72.55

Appendix E
Electron Donor Properties and Actual Delivery Calculations

Donor Properties*	Molecular Weight**	Specific Gravity***	Reference Temperatures	Solubility g donor/100g H20	Reference Temperature	
n-Butyric Acid (Butyrate)	88.1	0.964	20/4	miscible		
Benzoic Acid (Benzonate)	122.12	1.266	15/4	0.2	17	
Lactic Acid (Lactate)	90.08	1.249	15/4	miscible		
Propionic Acid (Propionate)	74.08	0.992	20/4	miscible		
n-propanol	60.09	0.804	20/4	miscible		
Toluene	92.13	0.866	20/4	0.05	16	
Spike cis-DCE****	96.94	1.29	15/4	0.35		V.P. mm Hg 200
Soil Test						
Acetate	60.05	1.049	20/4	miscible		
Sodium Chloride	58.44	2.163	20/4	35.7 39.8	0 100	
Carbon Dioxide	44.01	1.53	20/4	179.7cc 90.1cc	0 20	
Methane	16.01	0.5547 0.7491 0.415	0 18.7 184	0.4	20	

* Data taken form Perry's Chemical Engineer's Handbook, 7th Edition,
** Molecular Weights based on the 1941 Atomic Weight Values
*** Chemical density at given temperature referred to water at second temperature

Appendix F
Material and Chemical Inventory

	HAFB OU-1 Treatability Study Using Electon Donor Column Microcosms								
		8 Column System							
	1 w/just GW; 1 w/GW and Nutrients; 6 w/GW, Nutrients, and Donors								
#	Item Description	Vendor	Part/Vendor #	Vendor Phone #	Qty	Projected Unit Cost	Total Cost	Purchaser	Total Cost to USAF
F	True Ground Reservoir	Fisher	02-887-1	1-800-766-7000	1	133.40	133.40	Hill AFB	133.40
F	Main Feed/Sample Col	Fisher	02-887-5	1-800-766-7000	2	170.70	341.40	Hill AFB	341.40
F	5gl H20 Collection Carboys	Straw Ibis	Local		2	20.00	40.00	Self	Self Paid
F	Teflon Stopper Billets	Teftech	Custom	1-800-677-6854	3	100.00	100.00	Self	Self Paid
F	"O" Rings for Reservoirs	Ace Glass	7855-845	1-800-626-5381	2	20.89	41.78	Hill AFB	41.78
F	"O" Rings for Reservoirs	Ace Glass	7855-844	1-800-626-5381	1	20.00	20.00	Hill AFB	20.00
T	1/4" SS Tube 50' Coil	Alltech	30309	1-800-255-8324	2	190.00	380.00	Hill AFB	380.00
M	Manifold 1/4" T	Salt Lake Valve&Fit	SS-400-3	1-801-266-3560	6	15.70	94.20	Hill AFB	94.20
M	Manifold 1/4" Elbow	Salt Lake Valve&Fit	SS-400-9	1-801-266-3560	2	11.10	22.20	Hill AFB	22.20
P	Peristaltic Pump	Watson-Marlow	020.5524.00A	1-800-282-8823	1	4450.00	4450.00	Hill AFB	4450.00
P	Pump Mainfold Tubing	Watson-Marlow	984.0019.000	1-800-282-8823	2	39.50	79.00	Hill AFB	79.00
P	Pump Mainfold Tubing	Watson-Marlow	984.0013.000	1-800-282-8823	1	39.50	39.50	Hill AFB	39.50
P	Pump Mainfold Tubing	Watson-Marlow	984.0038.000	1-800-282-8823	1	39.50	39.50	Hill AFB	39.50
P	Pump Mainfold Tubing	Watson-Marlow	984.0142.000	1-800-282-8823	5	39.50	197.50	Hill AFB	197.50
F	Donor Feed Reservoir 12/cs	Fisher	06-421-13	1-800-766-7000	1	65.36	65.36	Hill AFB	65.36
F	Donor/Feed Line T 1/4"	Salt Lake Valve&Fit	SS-400-3	1-801-266-3560	6	15.70	94.20	Hill AFB	94.20
C	Glass Columns	Ace Glass	5820-37	1-800-626-5381	8	34.86	278.88	Hill AFB	278.88
C	Column End Fitting	Ace Glass	5802-37	1-800-626-5381	16	45.75	732.00	Hill AFB	732.00
C	Glass Wool	Alltech	4034	1-800-255-8324	2	23.00	46.00	Hill AFB	46.00
C	Swage Column/Tube Adapter	Salt Lake Valve&Fit	SS-400-1-4	1-801-266-3560	16	4.90	78.40	Hill AFB	78.40
P/C	17 Guage Needles	Fisher	14815605	1-800-766-7000	3	24.00	72.00	Hill AFB	72.00
P/C	33 Guage Needles	Fisher	14815621	1-800-766-7000	3	40.00	120.00	Hill AFB	120.00
P/C	Male Luer-1/4-28 Fitting	Fisher	NC-9436352	1-800-766-7000	32	13.50	432.00	Hill AFB	432.00
P/C	1/4"Swagelok Unions	Salt Lake Valve&Fit	SS-400-6	1-801-266-3560	2	7.60	15.20	Self	Self Paid
P/C	1/4"Swagelok Unions	Salt Lake Valve&Fit	SS-400-6	1-801-266-3560	30	7.60	228.00	Hill AFB	228.00
P/C	Swage Barbed Fittings	Salt Lake Valve&Fit	SS-405-2	1-801-266-3560	2	1.50	3.00	Self	Self Paid
P/C	Swage Barbed Fittings	Salt Lake Valve&Fit	SS-405-2	1-801-266-3560	30	1.50	45.00	Hill AFB	45.00
E	Effluent In-line/Sampler Btls	Fisher	05-719-121	1-800-766-7000	6	72.00	432.00	Hill AFB	432.00
E	Waste Reservoir	Fisher	02-961B	1-800-766-7000	1	56.00	56.00	Hill AFB	56.00
S	Tube Cutter	Alltech	13995	1-800-255-8324	1	49.00	49.00	Hill AFB	49.00
S	Tube Bender	Alltech	357090	1-800-255-8324	1	2.00	2.00	Hill AFB	2.00
F	Female 1/4-1/4Swage,N2 line	Salt Lake Valve&Fit	SS-400-7-4	1-801-266-3560	2	8.00	16.00	Hill AFB	16.00
F	Nitrogen Cylinder, 1 yr	Whitmore Gas		1-801-753-1111	1	70.00	15.00	USU	USU
F	Nitrogen Gas Refills	Whitmore Gas		1-801-753-1111	4	7.00	28.00	Self	Self Paid
F	N2 Combined Regulator	Whitmore Gas		1-801-753-1111	1	70.00	70.00	USU	USU
S	Mounting System	USU Shop			1	120.00	120.00	Self	Self Paid
E	Sample Syringe, 60 ml	Fisher			8	5.00	40.00	Self	Self Paid
F	Chemicals (see separate pg)				1	720.89	720.89	USU/UWRL	USU/UWRL
F	Glasswork				8	35.00	280.00	Hill AFB	280.00
F	Septum/Stopper	Chem Store			70	0.29	20.30	Self	Self Paid
F	3/4" Tygon Tubing	Chem Store			6	2.75	16.50	USU	USU
	Local Sampling Glassware	UWRL			1	200.00	200.00	USU/UWRL	USU/UWRL
	Soil Testing Setups	UWRL			12	30.00	360.00	UWRL	USSU/UWRL
	Total AF Allowed $8955			TOTAL COST			10054.21		8865.32

Appendix F
Material and Chemical Inventory

	HAFB OU-1 Treatability Study Using Electon Donor Column Microcosms								
		8 Column System							
	1 w/just GW; 1 w/GW and Nutrients; 6 w/GW, Nutrients, and Donors								
#	Item Description	Vendor	Part/Vendor #	Vendor Phone #	Qty	Projected Unit Cost	Total Cost	Purchaser	
	Donors								
	n-Propanol	Mallinckrodt	7169 (500ml)		1	4.71	4.71	USU	
	Propionic Acid	Mallinckrodt	7179 (500ml)		1	5.78	5.78	USU	
	Lactic Acid	Fisher	A162-500 (500ml)	1-201-796-7100	1	6.87	6.87	USU	
	Butyric Acid	Acros	10800-100 (100ml)	1-800-227-6764	1	10.64	10.64	USU	
	Benzoic Acid	Fisher	A-65 (100g)	1-201-796-7100	0	8.00	0.00	UWRL	
	Toluene	Fisher	T290-1 (1000ml)	1-201-796-7101	0	10.65	0.00	UWRL	
	Vitamin Solution								
	d-biotin	Sigma	B 4501 (10g)	1-800-325-3010	1	264.80	264.80	USU	
	folic acid	Acros	21663-0100 (10g)	1-800-227-6764	1	11.30	11.30	USU	
	pyridoxine hydrochloride	Acros	15077-0500 (50g)	1-800-227-6764	1	24.55	24.55	USU	
	thiamin hydrochloride	Sigma	T 4625 (25g)	1-800-325-3010	0	10.30	0.00	UWRL	
	riboflavin	Kodak	5181 (100g)	1-800-325-3010	0	8.05	0.00	UWRL	
	nicotinic acid	Aldrich	N785-0 (100g)	1-800-325-3010	0	8.45	0.00	UWRL	
	DL-calcium pantothenate	Sigma	P 5710 (25g)	1-800-325-3010	2	21.40	42.80	USU	
	Vitamin B^{12} (cyanocobalamin)	Sigma	V 2876 (5g)	1-800-325-3010	1	162.25	162.25	USU	
	p-aminobenzoic acid	Sigma	A 0129 (100g)	1-800-325-3010	1	20.96	20.96	USU	
	lipoic acid	Acros	13872-0250 (25g)	1-800-227-6764	1	120.39	120.39	USU	
	Ammendments								
	resazurin	Sigma	R 2127 (1g)	1-800-325-3010	1	10.23	10.23	USU	
	yeast	Sigma	YSC-1 (100g)	1-800-325-3010	1	23.38	23.38	USU	
	sodium bicarbonate	Sigma	S 6014 (500g)	1-800-325-3010	0	13.40	0.00	UWRL	
	Shipping					12.23	12.23		
						779.74	720.89	USU Total	
	cis Dichloroethene	Supelco	48597 (LA-78817)(1g)	1-814-359-3441	1	44.91	44.91	Self	
						824.65	765.80	Grand Total	
	Note* Qty 0 denotes chemicals obtained from UWRL excess								

Appendix G
Column Flow Calculations and Microcosm HRTs

Hill AFB, OU-1 Column Study

From Comprehensive RI Report for OU-1 Dec 95
Groundwater Horizontal Linear Velocity pg 5-18
Per Telecon w/Deborah Drain of Montgomery Watson, values include porosity
ie velocity stated is (Q/A)/porosity

	Low	High	Average
	310 ft/yr	4656 ft/yr	1950 ft/yr
becomes	0.85 ft/dy	12.76 ft/dy	5.3 ft/dy
	0.018 cm/mir	0.27 cm/min	0.113 cm/min

Assume Porosity = 0.4

0.0072 cm/m	0.108 cm/min	0.045 cm/min

Average Darcy Velocity
0.045 cm/min

Column Dimensions

ID = 25 mm = D — Area = $(pD^2)/4$ = 490.87 mm^2

Length = 600 mm — Volume = $((pD^2)/4)L$ 0.295 L

Col Area	4.91 cm^2
Col Vol	294.6 cm^3

Primary Flow Rate Using Average Velocity
(Interstitial = Q/A/e)
Flow * Area = 0.113 * 4.91 cm^2 = 0.5499 cm^3/min = 0.550 ml/min

(Darcy)
Flow * Area = 0.045 * 4.91 cm^2 = 0.221 cm^3/min =

Solution Flow Rate
0.221 ml/min

Flow per column per week = 2.23 L/wk

Donor Flow Rate:
0.221 cm^3/min * 5% = 0.011 ml/min =

Donor Flow Rate
110.9 ml/wk
0.011 ml/min

1/4" 316 Stainless Steel Tubing Area
Area = $(pD^2)/4$ = 0.317 cm^2
Q/A = (0.221 cm^3/min)/0.317 cm^2 = 0.697 cm/min

HRT: Empty Bed Column, Ideal Flow
Flow = 0.221 + .011 = 0.232
HRT = Col Vol/Flow 294.6 cm^3 /0.232 ml/min =

HRT in mins	HRT in day
1269.8	0.882

HRT: Actual Microcosm Values Based on Prototype Measured Values
Flow = 0.2234 + 0.0 = 0.2278
HRT = Col Vol/Flow 294.6 cm^3 /0.2278 ml/min =

1293.24	0.898

Corrected for porosity; assume porosity is 0.4 for the sandy soil
HRT = Col Vol/Flow*porosity (294.6/0.2278)*0.4 =

517.30	0.359

Appendix G
Column Flow Calculations and Microcosm HRTs

HRT: Actual Microcosm Values

Column Cross Sectional Area = 490.87mm^2
Column Height = 600 mm
Assume Porosity = 0.4
Col Vol = 294.6 cm3

HRT = Col Vol/Flow

Corrected for porosity; assume porosity is 0.4 for the sandy soil

HRT = (Col Vol*porosity/Flow)

		Groundwater	Amended	n-Butyrate	Benzoate	Lactate	Propionate	n-Propanol	Toluene
	Column Area (cm^2)	4.91	4.91	4.91	4.91	4.91	4.91	4.91	4.91
	Sediment Depth (inches)	16.75	17.25	18.25	17.75	16.75	18.75	18.00	18.25
	Sediment Depth (cm)	42.55	43.82	46.36	45.09	42.55	47.63	45.72	46.36
	Sediment Volume (cm3)	208.84	215.07	227.54	221.31	208.84	233.78	224.43	227.54
	Water Volume in Sediment (cm^3)	17.02	17.53	18.54	18.03	17.02	19.05	18.29	18.54
	Supernatant Depth	17.46	16.19	13.65	14.92	17.46	12.38	14.28	13.65
	Water Volumn in Supernatant (cm^3)	85.68	79.45	66.98	73.21	85.68	60.75	70.10	66.98
	Total Water Volume (cm^3)	102.70	96.97	85.52	91.25	102.70	79.80	88.38	85.52
Date									
22-Nov	Measured Flow (ml/min)	0.250	0.260	0.242	0.232	0.235	0.229	0.257	0.250
	HRT (min)	410.797	372.974	353.393	393.307	437.019	348.450	343.908	342.085
	HRT(day)	0.285	0.259	0.245	0.273	0.303	0.242	0.239	0.238
11-Jan	Measured Flow (ml/min)	0.215	0.223	0.234	0.226	0.266	0.215	0.212	0.212
	HRT(min)	477.671	434.858	365.475	403.749	386.088	371.140	416.907	403.402
	HRT (day)	0.332	0.302	0.254	0.280	0.268	0.258	0.290	0.280
1-Feb	Measured Flow (ml/min)	0.211	0.228	0.228	0.241	0.231	0.224	0.224	0.241
	HRT(min)	486.727	425.322	375.093	378.619	444.586	356.228	394.572	354.860
	HRT (day)	0.338	0.295	0.260	0.263	0.309	0.247	0.274	0.246
Ave Flow		0.225	0.237	0.235	0.233	0.244	0.223	0.231	0.234
Overall Average Flow									0.233
Deviation from Average Flow		0.007	-0.004	-0.002	0.000	-0.011	0.010	0.002	-0.002

Appendix H
pH Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

					Groundwater Amended with Nutrient/Yeast and Electron Donor						
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
13-Jun-98		6.94		6.97							
1-Jul-98		7.03									
25-Jul-98		7.40		7.44							
10-Aug-98	1										
9-Sep-98	31	7.07	7.18	7.05	6.84	6.74	6.77	6.66	6.84	6.79	6.78
10-Sep-98	32	7.12	7.40	7.05	7.19	7.00	7.10	6.90	6.99	7.07	7.19
15-Sep-98	37	7.07	7.27	7.15	7.14	6.92	7.02	6.96	7.00	7.00	7.11
24-Sep-98	46	7.31	7.40	7.33	7.28	6.97	7.04	7.12	7.04	7.21	7.29
1-Oct-98	53	7.26	7.19	6.99	7.07	6.75	6.85	7.01	6.91	7.07	7.09
8-Oct-98	60	7.46	9.36	7.28	9.08	8.32	8.62	9.03	8.81	9.06	9.11
15-Oct-98	67	7.29	8.32	7.29	9.10	8.88	8.89	9.17	9.17	9.21	9.25
22-Oct-98	74	7.23	9.05	7.10	9.02	8.55	8.58	8.57	9.02	9.07	9.13
29-Oct-98	81	7.26	8.40	7.38	9.03	9.06	8.77	8.53	9.10	9.14	9.20
5-Nov-98	88	7.38	7.77	7.16	8.88	8.88	8.46	7.95	8.79	8.96	9.06
12-Nov-98	95	7.60	7.95	7.15	8.88	8.79	8.02	7.73	8.85	8.84	8.85
19-Nov-98	102	7.65	9.33	7.33	9.06	8.70	8.40	7.80	8.73	8.99	9.07
25-Nov-98	108	7.40	8.73	7.46	9.33	9.11	8.87	8.82	9.03	9.42	9.53
3-Dec-98	116	7.30	9.18	7.38	9.31	9.03	8.94	8.79	8.95	9.33	9.43
10-Dec-98	123	7.27	9.30	7.39	9.19	8.72	8.84	8.67	8.85	9.24	9.33
17-Dec-98	130	7.32	8.87	7.38	9.08	8.56	8.64	8.54	8.60	9.05	9.16
24-Dec-98	137	7.22	8.10	7.30	9.17	8.68	8.67	8.80	8.94	9.16	9.22
31-Dec-98	144	7.38	9.21	7.38	9.08	8.51	8.76	8.74	8.95	9.06	9.16
7-Jan-99	151	7.11	9.14	7.29	8.78	7.61	8.40	8.19	8.39	8.72	8.76
14-Jan-99	158	7.29	8.61	7.28	9.15	9.02	8.95	8.99	8.99	9.23	9.25
21-Jan-99	165	7.41	8.08	7.26	9.34	9.09	9.17	9.07	9.21	9.41	9.23
25-Jan-99	169	7.26	7.18	7.12	7.81	7.16	7.12	7.06	7.28	7.82	7.88
28-Jan-99	172	7.17	7.30	7.44	7.39	6.94	7.02	6.84	7.08	7.41	7.64
4-Feb-99	179	7.37	7.37	7.24	7.20	6.90	7.07	6.72	7.10	6.99	7.33
12-Feb-99	187	7.60	7.59	7.54	7.33	6.90	6.98	6.84	7.10	7.05	7.29
17-Feb-99	192	7.58	7.38	7.15	7.21	6.64	6.86	6.73	6.95	6.92	7.14
24-Feb-99	199	7.55	7.63	7.22	7.35	6.73	7.04	6.89	7.16	7.21	7.37

Appendix H
Dissolved Oxygen Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Results as ppm O_2

					Groundwater Amended with Nutrient/Yeast and Electron Donor						
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
13-Jun-98		3.37		2.34							
25-Jul-98		1.10									
25-Jul-98		1.25		0.86							
10-Aug-98	1										
10-Sep-98	32	0.79	0.30	1.04	0.17	0.22	0.11	0.24	0.23	0.11	0.23
15-Sep-98	37	1.38	0.60	1.41	0.42	0.37	0.32	0.40	0.42	0.29	0.34
24-Sep-98	46	3.12	0.51	1.90	0.36	0.45	0.36	0.49	0.48	0.29	0.22
1-Oct-98	53	1.24	0.33	1.44	0.11	0.13	0.12	0.13	0.16	0.16	0.19
8-Oct-98	60	1.81	0.31	1.31	0.27	0.24	0.19	0.15	0.16	0.15	0.14
15-Oct-98	67	2.05	0.39	1.27	0.20	0.11	0.17	0.14	0.11	0.09	0.10
22-Oct-98	74	1.60	0.95	1.36	0.19	0.15	0.12	0.12	0.08	0.15	0.11
29-Oct-98	81	1.53	0.26	1.31	0.19	0.08	0.09	0.12	0.12	0.11	0.15
5-Nov-98	88	1.90	0.88	1.31	0.25	0.22	0.19	0.19	0.19	0.17	0.19
12-Nov-98	95	1.29	1.19	1.42	0.21	0.17	0.19	0.14	0.16	0.13	0.22
19-Nov-98	102	1.43	1.77	1.38	0.24	0.18	0.16	0.14	0.13	0.13	0.13
25-Nov-98	108	1.80	0.80	1.20	0.23	0.22	0.19	0.17	0.17	0.15	0.15
3-Dec-98	116	1.76	0.81	1.22	0.26	0.21	0.17	0.17	0.15	0.16	0.14
10-Dec-98	123	2.02	0.51	1.30	0.34	0.25	0.23	0.24	0.23	0.23	0.21
17-Dec-98	130	1.34	0.94	1.48	0.33	0.26	0.22	0.22	0.21	0.19	0.20
24-Dec-98	137	2.32	1.27	1.26	0.24	0.20	0.19	0.18	0.17	0.16	0.16
31-Dec-98	144	2.38	1.17	1.54	0.27	0.21	0.62	0.18	0.57	0.30	0.49
7-Jan-99	151	1.62	1.08	1.32	0.32	0.31	0.28	0.27	0.29	0.28	0.32
14-Jan-99	158	2.70	2.70	1.38	0.54	0.28	0.28	0.82	0.47	0.83	0.61
21-Jan-99	165	2.76	1.44	1.35	0.32	0.27	0.30	0.34	0.29	0.22	0.31
25-Jan-99	169	1.67	0.61	1.04	0.33	0.34	0.35	0.32	0.36	0.34	0.33
28-Jan-99	172	1.38	0.36	1.54	0.31	0.43	0.34	0.35	0.30	0.31	0.32
4-Feb-99	179	1.71	0.31	1.32	0.34	0.33	0.20	0.41	0.27	0.41	0.26
12-Feb-99	187	1.91	0.52	1.09	0.30	0.24	0.36	0.29	0.27	0.39	0.25
17-Feb-99	192	2.01	0.56	1.32	0.41	0.37	0.29	0.49	0.34	0.46	0.48
24-Feb-99	199	1.55	0.45	1.53	0.56	0.49	0.46	0.49	0.52	0.50	0.60

Appendix H
Dissolved Oxygen Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Percentage Removal Efficiencies — Groundwater Amended with Nutrient/Yeast and Electron Donor

Date	Experiment Day	Unamended Groundwater Effluent (Col 1)	Nutrient/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1								
10-Sep-98	32	-31.65	43.33	26.67	63.33	20.00	23.33	63.33	23.33
15-Sep-98	37	-2.17	30.00	38.33	46.67	33.33	30.00	51.67	43.33
24-Sep-98	46	39.10	29.41	11.76	29.41	3.92	5.88	43.14	56.86
1-Oct-98	53	-16.13	66.67	60.61	63.64	60.61	51.52	51.52	42.42
8-Oct-98	60	27.62	12.90	22.58	38.71	51.61	48.39	51.61	54.84
15-Oct-98	67	38.05	48.72	71.79	56.41	64.10	71.79	76.92	74.36
22-Oct-98	74	15.00	80.00	84.21	87.37	87.37	91.58	84.21	88.42
29-Oct-98	81	14.38	26.92	69.23	65.38	53.85	53.85	57.69	42.31
5-Nov-98	88	31.05	71.59	75.00	78.41	78.41	78.41	80.68	78.41
12-Nov-98	95	-10.08	82.35	85.71	84.03	88.24	86.55	89.08	81.51
19-Nov-98	102	3.50	86.44	89.83	90.96	92.09	92.66	92.66	92.66
25-Nov-98	108	33.33	71.25	72.50	76.25	78.75	78.75	81.25	81.25
3-Dec-98	116	30.68	67.90	74.07	79.01	79.01	81.48	80.25	82.72
10-Dec-98	123	35.64	33.33	50.98	54.90	52.94	54.90	54.90	58.82
17-Dec-98	130	-10.45	64.89	72.34	76.60	76.60	77.66	79.79	78.72
24-Dec-98	137	45.69	81.10	84.25	85.04	85.83	86.61	87.40	87.40
31-Dec-98	144	35.29	76.92	82.05	47.01	84.62	51.28	74.36	58.12
7-Jan-99	151	18.52	70.37	71.30	74.07	75.00	73.15	74.07	70.37
14-Jan-99	158	48.89	80.00	89.63	89.63	69.63	82.59	69.26	77.41
21-Jan-99	165	51.09	77.78	81.25	79.17	76.39	79.86	84.72	78.47
25-Jan-99	169	37.72	45.90	44.26	42.62	47.54	40.98	44.26	45.90
28-Jan-99	172	-11.59	13.89	-19.44	5.56	2.78	16.67	13.89	11.11
4-Feb-99	179	22.81	-9.68	-6.45	35.48	-32.26	12.90	-32.26	16.13
12-Feb-99	187	42.93	42.31	53.85	30.77	44.23	48.08	25.00	51.92
17-Feb-99	192	34.33	26.79	33.93	48.21	12.50	39.29	17.86	14.29
24-Feb-99	199	1.29	-24.44	-8.89	-2.22	-8.89	-15.56	-11.11	-33.33
	Ave Removal	20.19	49.87	54.28	58.71	53.01	55.48	57.16	56.07

Appendix H
Alkalinity Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Results as mg/L of $CaCO_3$

				Groundwater Amended with Nutrient/Yeast and Electron Donor								
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)	
13-Jun-98												
1-Jul-98		50										
25-Jul-98		62		64								
10-Aug-98	1											
10-Sep-98	32	515	1081	566	1040	1071	1040	1081	1030	1040	1050	
15-Sep-98	37	515	970	495	1030	1010	990	1030	1040	1081	1040	
24-Sep-98	46	485	980	444	980	939	990	980	949	970	1000	
1-Oct-98	53	404	980	424	919	949	1020	990	949	1000	990	
8-Oct-98	60	411	1380	401	949	851	803	910	881	891	920	
15-Oct-98	67	411	685	431	1037	920	910	812	1008	940	979	
22-Oct-98	74	470	998	490	1018	1008	910	979	1028	1018	1018	
29-Oct-98	81	391	568	480	1116	1096	1008	1008	1116	1106	1106	
5-Nov-98	88	421	587	401	1184	1057	988	1076	1096	1116	1135	
12-Nov-98	95	352	548	362	930	822	773	851	881	861	881	
19-Nov-98	102	382	998	577	891	812	812	832	832	861	851	
25-Nov-98	108	372	675	372	1067	959	842	969	959	1047	1106	
3-Dec-98	116	397	925	509	1078	997	915	1007	1007	1037	1047	
10-Dec-98	123	417	1129	397	1047	1007	966	1017	1007	1037	1037	
17-Dec-98	130	376	814	397	1068	976	915	986	1007	1047	1078	
24-Dec-98	137	427	610	386	1271	1078	956	1119	1159	1251	1190	
31-Dec-98	144	427	1129	427	1088	1027	997	1058	1088	1068	1080	
7-Jan-99	151	437	1078	397	1058	1108	966	945	1017	1017	1037	
14-Jan-99	158	407	814	390	1288	1305	1203	1322	1322	1305	1254	
21-Jan-99	165	427	641	417	1363	1200	1119	1210	1251	1505	1210	
25-Jan-99	169	393	953	383	962	972	913	953	962	972	933	
28-Jan-99	172	422	894	383	933	884	835	884	903	903	845	
4-Feb-99	179	363	913	383	894	874	835	894	894	874	874	
12-Feb-99	187	354	923	344	903	874	825	854	903	864	864	
17-Feb-99	192	363	874	354	894	766	786	845	845	864	815	
24-Feb-99	199	383	884	471	805	845	825	835	864	884	854	

Appendix H
cis 1,2-Dichloroethene Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Results in ug/L

					Groundwater Amended with Nutrient/Yeast and Electron Donor						
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1										
9-Sep-98	31	2736.22	2363.56	2424.12	2260.68	2203.72	2164.96	2189.84	2124.44	2220.68	2169.48
30-Sep-98	52	59.98	66.86	66.00	65.45	63.02	59.34	64.67	61.27	56.96	60.09
20-Oct-98	72	42.15	50.69	37.16	45.49	43.81	41.00	41.28	46.09	44.15	40.89
10-Nov-98	93	29.78	25.50	25.30	25.21	26.07	23.44	21.65	21.37	24.02	26.42
2-Dec-98	115	25.50	11.76	9.77	10.70	10.26	9.78	21.37	9.54	11.14	9.62
23-Dec-98	136	150.93	119.14	105.98	92.33	93.10	78.05	94.39	79.56	85.39	89.03
30-Dec-98	143	414.98	138.13	276.06	117.52	110.90	105.69	115.52	136.76	124.83	124.83
6-Jan-99	150	220.09	255.24	228.93	190.59	204.31	169.11	208.43	173.34	206.76	211.78
14-Jan-99	158	245.65	143.93	123.27	242.44	362.40	321.03	354.86	337.72	277.99	401.79
21-Jan-99	165	336.96	135.90	163.16	116.42	115.88	106.28	105.47	106.70	107.08	98.04
27-Jan-99	171	132.20	172.05	134.12	166.81	172.33	172.02	170.86	107.08	170.13	153.50
3-Feb-99	178	141.27	180.57	141.89	180.67	180.24	162.26	174.45	175.30	167.53	157.99
10-Feb-99	185	379.46	218.98	424.80	220.02	207.61	172.33	211.69	195.80	192.78	187.19
17-Feb-99	192	486.31	663.25	419.39	203.31	640.22	571.86	600.42	640.26	564.49	583.10
24-Feb-99	199	393.79	556.66	364.99	533.35	521.11	489.02	502.05	525.21	537.09	522.30

Appendix H
cis 1,2-Dichloroethene Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Percentage Removal Efficiencies — Groundwater Amended with Nutrient/Yeast and Electron Donor

Date	Experiment Day	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
9-Sep-98	31	11.41	4.35	6.76	8.40	7.35	10.12	6.05	8.21
30-Sep-98	52	-10.04	2.11	5.74	11.25	3.28	8.36	14.81	10.13
20-Oct-98	72	11.84	10.26	13.57	19.12	18.56	9.07	12.90	19.33
10-Nov-98	93	15.04	1.14	-2.24	8.08	15.10	16.20	5.80	-3.61
2-Dec-98	115	61.69	9.01	12.76	16.84	-81.72	18.88	5.27	18.20
23-Dec-98	136	29.78	22.50	21.86	34.49	20.77	33.22	28.33	25.27
30-Dec-98	143	33.48	14.92	19.71	23.49	16.37	0.99	9.63	9.63
6-Jan-99	150	-4.02	25.33	19.95	33.74	18.34	32.09	18.99	17.03
14-Jan-99	158	49.82	-68.44	-151.79	-123.05	-146.55	-134.64	-93.14	-179.16
21-Jan-99	165	51.58	14.33	14.73	21.80	22.39	21.49	21.21	27.86
27-Jan-99	171	-1.45	3.05	-0.16	0.02	0.69	37.76	1.12	10.78
3-Feb-99	178	-0.44	-0.06	0.18	10.14	3.39	2.92	7.22	12.50
10-Feb-99	185	-11.95	-0.47	5.19	21.30	3.33	10.59	11.96	14.52
17-Feb-99	192	13.76	69.35	3.47	13.78	9.47	3.47	14.89	12.08
24-Feb-99	199	7.31	4.19	6.39	12.15	9.81	5.65	3.52	6.17
	Range	-10/62%	-68/69%	-152/22%	-123/34%	-147/22%	-134/38%	-93/28%	-179/25%
	Span	72.00	137.00	174.00	157.00	169.00	172.00	121.00	204.00
	Ave	17.19	7.44	-1.59	7.44	-5.29	5.08	4.57	0.60
Range Without Day 158		-10/62%	0/69%	-2/22%	0/34%	-81/22%	1/38%	1/28%	-4/25%
Span		72.00	69.00	24.00	34.00	103.00	37.00	27.00	29.00
Ave Without Day 158		14.86	12.86	9.14	16.76	4.80	15.06	11.55	13.44

Field Prediction from Column One	
Change in Concentration, Col 1(Inf-Eff): (ug/L)	Δ Concentration/ Distance Through Soil: (ug/L/cm)
312.10	7.33
-6.02	-0.14
4.99	0.12
4.48	0.11
15.73	0.37
44.95	1.06
138.92	3.26
-8.84	-0.21
122.38	2.88
173.80	4.08
-1.92	-0.05
-0.62	-0.01
-45.34	-1.07
66.92	1.57
28.80	0.68
Range	-1.07/7.33 ug/L/cm
Ave	1.33

Appendix H
cis 1,2-Dichloroethene Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Percentage Removal Rate (%/day) Groundwater Amended with Nutrient/Yeast and Electron Donor

Date	Experiment Day	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
9-Sep-98	31								
30-Sep-98	52	0.03	0.15	0.30	0.47	0.25	0.44	0.50	0.44
20-Oct-98	72	0.05	0.31	0.48	0.76	0.55	0.44	0.69	0.74
10-Nov-98	93	0.64	0.27	0.27	0.65	0.80	0.60	0.45	0.37
2-Dec-98	115	1.74	0.23	0.24	0.57	-1.51	0.80	0.25	0.33
23-Dec-98	136	2.18	0.75	0.82	1.22	-1.45	1.24	0.80	1.04
30-Dec-98	143	4.52	2.67	2.97	4.14	2.65	2.44	2.71	2.49
6-Jan-99	150	2.10	2.87	2.83	4.09	2.48	2.36	2.04	1.90
14-Jan-99	158	2.86	-2.69	-8.24	-5.58	-8.01	-6.41	-4.63	-10.13
21-Jan-99	165	7.24	-3.86	-9.79	-7.23	-8.87	-8.08	-5.14	-10.81
27-Jan-99	171	4.18	1.45	1.21	1.82	1.92	4.94	1.86	3.22
3-Feb-99	178	-0.14	0.21	0.00	0.73	0.29	2.91	0.60	1.66
10-Feb-99	185	-0.88	-0.04	0.38	2.25	0.48	0.96	1.37	1.93
17-Feb-99	192	0.13	4.92	0.62	2.51	0.91	1.00	1.92	1.90
24-Feb-99	199	1.51	5.25	0.70	1.85	1.38	0.65	1.31	1.30
	Range	-0.1/7.2%	-3.9/5.3%	-9.8/3.0%	-7.2/4.1%	-8.9/2.7%	-8.1/4.9%	-5.1/2.7%	-10.8/3.2%
	Span	7.38	9.11	12.76	11.37	11.52	13.02	7.85	14.03
	Ave	1.87	0.89	-0.51	0.59	-0.58	0.31	0.34	-0.26
Ave Without Day 158		1.79	1.17	0.08	1.06	-0.01	0.82	0.72	0.50

Appendix H
Vinyl Chloride Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Results in ug/L

						Groundwater Amended with Nutrient/Yeast and Electron Donor					
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1										
9-Sep-98	31	295.37	244.12	270.43	262.23	261.11	270.43	256.49	265.47	270.95	279.99
30-Sep-98	52	32.82	33.56	68.66	65.57	65.57	58.02	63.59	54.22	45.81	64.63
20-Oct-98	72	N/D	46.00	36.81	53.93	65.79	53.27	53.45	60.36	58.98	50.90
10-Nov-98	93	N/D	N/D	N/D	27.40	23.90	24.21	18.67	16.49	17.22	15.53
2-Dec-98	115	N/D	8.39	N/D	N/D	10.19	9.19	16.49	8.74	9.10	9.12
23-Dec-98	136	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
30-Dec-98	143	N/D	N/D	3.46	N/D	N/D	N/D	N/D	N/D	N/D	N/D
6-Jan-99	150	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
14-Jan-99	158	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
21-Jan-99	165	N/D	N/D	3.29	N/D	N/D	N/D	N/D	N/D	N/D	N/D
27-Jan-99	171	N/D	N/D	9.10	4.43	4.63	N/D	N/D	N/D	N/D	N/D
3-Feb-99	178	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
10-Feb-99	185	N/D	N/D	N/D	2.28	N/D	4.63	N/D	N/D	N/D	N/D
17-Feb-99	192	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
24-Feb-99	199	N/D	N/D	25.56	N/D	N/D	N/D	N/D	N/D	N/D	N/D

Appendix H
Vinyl Chloride Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Zero Value Listed Instead of N/D

Results in ug/L

					Groundwater Amended with Nutrient/Yeast and Electron Donor						
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1										
9-Sep-98	31	295.37	244.12	270.43	262.23	261.11	270.43	256.49	265.47	270.95	279.99
30-Sep-98	52	32.82	33.56	68.66	65.57	65.57	58.02	63.59	54.22	45.81	64.63
20-Oct-98	72	0.00	46.00	36.81	53.93	65.79	53.27	53.45	60.36	58.98	50.90
10-Nov-98	93	0.00	0.00	0.00	27.40	23.90	24.21	18.67	16.49	17.22	15.53
2-Dec-98	115	0.00	8.39	0.00	0.00	10.19	9.19	16.49	8.74	9.10	9.12
23-Dec-98	136	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30-Dec-98	143	0.00	0.00	3.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6-Jan-99	150	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14-Jan-99	158	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21-Jan-99	165	0.00	0.00	3.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27-Jan-99	171	0.00	0.00	9.10	4.43	4.63	0.00	0.00	0.00	0.00	0.00
3-Feb-99	178	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10-Feb-99	185	0.00	0.00	0.00	2.28	0.00	4.63	0.00	0.00	0.00	0.00
17-Feb-99	192	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24-Feb-99	199	0.00	0.00	25.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix H
Vinyl Chloride Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

%Apparent Removal Efficiencies

Groundwater Amended with Nutrient/Yeast and Electron Donor

Date	Experiment Day	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
9-Sep-98	31	8.44	-7.42	-6.96	-10.78	-5.07	-8.75	-10.99	-14.69
30-Sep-98	52	-109.20	-95.38	-95.38	-72.88	-89.48	-61.56	-36.50	-92.58
20-Oct-98	72	0.00	-17.24	-43.02	-15.80	-16.20	-31.22	-28.22	-10.65
10-Nov-98	93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2-Dec-98	115	0.00	100.00	-21.45	-9.54	-96.54	-4.17	-8.46	-8.70
23-Dec-98	136	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30-Dec-98	143	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6-Jan-99	150	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14-Jan-99	158	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21-Jan-99	165	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27-Jan-99	171	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3-Feb-99	178	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10-Feb-99	185	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17-Feb-99	192	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24-Feb-99	199	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Range	-109/8%	-95/100%	-95100%	-72/0%	-97/0%	-62/0%	-37/0%	-93/0%
	Ave	-6.72	-1.34	-11.12	-7.27	-13.82	-7.05	-5.61	-8.44
Ave Accumulation (First 5 days)		-21.84	-2.52	-31.97	-19.64	-40.44	-19.39	-14.64	-22.39

Appendix H
Ethene Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Results as mg/L — Groundwater Amended with Nutrient/Yeast and Electron Donor

Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)	Detection Limit
10-Aug-98	1											
9-Sep-98	31	0.010	0.011	**0.009**	**0.008**	0.011	0.011	0.011	**0.009**	**0.007**	0.012	0.1
30-Sep-98	52	0.010	0.011	0.010	0.018	0.019	0.013	0.013	0.012	0.014	0.013	0.01
20-Oct-98	72	0.018	0.023	0.018	0.039	0.029	0.029	0.020	0.010	0.021	0.010	0.01
10-Nov-98	93	0.0096	0.0096	0.0096	0.0130	0.0096	0.0096	0.0096	0.0096	0.0096	0.0100	0.0096
2-Dec-98	115	0.010	0.020	0.010	0.020	0.010	0.010	0.011	0.010	0.015	0.015	0.01
23-Dec-98	136	0.014	0.024	0.014	0.010	0.021	0.017	0.025	0.024	0.016	0.014	0.01
30-Dec-98	143	0.010	0.040	0.010	0.048	0.045	0.031	0.028	0.033	0.032	0.034	0.01
6-Jan-99	150	0.010	0.024	0.010	0.017	0.019	0.016	0.020	0.018	0.012	0.019	0.01
14-Jan-99	158	0.010	0.045	0.010	0.010	**0.008**	0.016	0.018	0.012	0.010	**0.009**	0.01
21-Jan-99	165	0.015	0.022	0.010	0.010	0.010	0.010	0.011	**0.009**	0.011	0.011	0.01
27-Jan-99	171	0.010	0.016	0.010	0.023	0.023	0.020	0.014	0.014	0.015	0.021	0.01
3-Feb-99	178	0.010	0.014	0.010	0.016	0.011	0.014	0.013	0.010	0.014	0.021	0.01
10-Feb-99	185	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
17-Feb-99	192	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
24-Feb-99	199	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010

Appendix H
Ethene Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Percentage Removal Efficiencies — Groundwater Amended with Nutrient/Yeast and Electron Donor

Date	Experiment Day	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1								
9-Sep-98	31	10.00	27.27	0.00	0.00	0.00	18.18	36.36	-9.09
30-Sep-98	52	0.00	-63.64	-72.73	-18.18	-18.18	-9.09	-27.27	-18.18
20-Oct-98	72	0.00	-69.57	-26.09	-26.09	13.04	56.52	8.70	56.52
10-Nov-98	93	0.00	-35.42	0.00	0.00	0.00	0.00	0.00	-4.17
2-Dec-98	115	0.00	0.00	50.00	50.00	45.00	50.00	25.00	25.00
23-Dec-98	136	0.00	58.33	12.50	29.17	-4.17	0.00	33.33	41.67
30-Dec-98	143	0.00	-20.00	-12.50	22.50	30.00	17.50	20.00	15.00
6-Jan-99	150	0.00	29.17	20.83	33.33	16.67	25.00	50.00	20.83
14-Jan-99	158	0.00	77.78	82.22	64.44	60.00	73.33	77.78	80.00
21-Jan-99	165	33.33	54.55	54.55	54.55	50.00	59.09	50.00	50.00
27-Jan-99	171	0.00	-43.75	-43.75	-25.00	12.50	12.50	6.25	-31.25
3-Feb-99	178	0.00	-14.29	21.43	0.00	7.14	28.57	0.00	-50.00
10-Feb-99	185	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17-Feb-99	192	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24-Feb-99	199	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Range	0/33%	-70/78%	-73/82%	-26/64%	-18/60%	-9/73%	-27/78%	-50/80%
	AveRemoval	2.89	0.03	5.76	12.31	14.13	22.11	18.68	11.76

Appendix H
Ethane Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Results as mg/L

			Groundwater Amended with Nutrient/Yeast and Electron Donor									
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)	Detection Limit
10-Aug-98	1											
9-Sep-98	31	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
30-Sep-98	52	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.01
20-Oct-98	72	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
10-Nov-98	93	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
2-Dec-98	115	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
23-Dec-98	136	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
30-Dec-98	143	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
6-Jan-99	150	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
14-Jan-99	158	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
21-Jan-99	165	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
27-Jan-99	171	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
3-Feb-99	178	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
10-Feb-99	185	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
17-Feb-99	192	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
24-Feb-99	199	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008

Appendix H
Ethane Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination
Percentage Removal Efficiencies Groundwater Amended with Nutrient/Yeast and Electron Donor

Date	Experiment Day	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1								
9-Sep-98	31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30-Sep-98	52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20-Oct-98	72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10-Nov-98	93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2-Dec-98	115	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23-Dec-98	136	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30-Dec-98	143	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6-Jan-99	150	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14-Jan-99	158	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21-Jan-99	165	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27-Jan-99	171	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3-Feb-99	178	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10-Feb-99	185	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17-Feb-99	192	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24-Feb-99	199	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix H
Methane Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Results as mg/L

			Groundwater Amended with Nutrient/Yeast and Electron Donor									
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)	Detection Limit
10-Aug-98	1											
9-Sep-98	31	0.594	0.349	0.470	0.412	0.597	0.585	0.588	0.415	0.370	0.678	0.004
30-Sep-98	52	0.056	0.226	0.211	0.576	0.523	0.546	0.411	0.333	0.528	0.393	0.004
20-Oct-98	72	0.311	0.453	0.048	0.398	0.272	0.424	0.244	0.223	0.380	0.039	0.004
10-Nov-98	93	0.055	0.075	0.169	0.333	0.209	0.217	0.152	0.100	0.125	0.348	0.004
2-Dec-98	115	0.187	0.432	0.039	0.326	0.038	0.116	0.142	0.181	0.255	0.172	0.004
23-Dec-98	136	0.284	0.560	0.146	0.136	0.312	0.291	0.493	0.405	0.241	0.128	0.004
30-Dec-98	143	0.025	0.768	0.059	0.881	0.688	0.559	0.479	0.510	0.559	0.212	0.004
6-Jan-99	150	0.123	0.557	0.038	0.268	0.256	0.297	0.361	0.303	0.170	0.187	0.004
14-Jan-99	158	0.175	1.376	0.170	0.210	0.251	0.329	0.433	0.234	0.221	0.239	0.004
21-Jan-99	165	0.229	0.343	0.020	0.098	0.074	0.078	0.132	0.103	0.115	0.115	0.004
27-Jan-99	171	0.104	0.317	0.173	0.409	0.406	0.347	0.243	0.228	0.275	0.420	0.004
3-Feb-99	178	0.033	0.282	0.094	0.317	0.214	0.290	0.282	0.194	0.271	0.438	0.004
10-Feb-99	185	**0.004**	0.019	0.011	0.036	0.037	0.115	0.118	0.035	0.051	0.043	0.004
17-Feb-99	192	0.011	0.021	0.011	0.107	0.062	0.132	0.287	0.079	0.161	0.122	0.004
24-Feb-99	199	0.016	0.019	0.019	0.183	0.263	0.148	0.359	0.225	0.248	0.165	0.004

Appendix H
Methane Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination
Percentage Removal Efficiencies — Groundwater Amended with Nutrient/Yeast and Electron Donor

Date	Experiment Day	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1								
9-Sep-98	31	20.875	-18.052	-71.060	-67.622	-68.481	-18.911	-6.017	-94.269
30-Sep-98	52	-276.786	-154.867	-131.416	-141.593	-81.858	-47.345	-133.628	-73.894
20-Oct-98	72	84.566	12.141	39.956	6.402	46.137	50.773	16.115	91.391
10-Nov-98	93	-207.273	-344.000	-178.667	-189.333	-102.667	-33.333	-66.667	-364.000
2-Dec-98	115	79.144	24.537	91.204	73.148	67.130	58.102	40.972	60.185
23-Dec-98	136	48.592	75.714	44.286	48.036	11.964	27.679	56.964	77.143
30-Dec-98	143	-136.000	-14.714	10.417	27.214	37.630	33.594	27.214	72.396
6-Jan-99	150	69.106	51.885	54.039	46.679	35.189	45.601	69.479	66.427
14-Jan-99	158	2.857	84.738	81.759	76.090	68.532	82.994	83.939	82.631
21-Jan-99	165	91.266	71.429	78.426	77.259	61.516	69.971	66.472	66.472
27-Jan-99	171	-66.346	-29.022	-28.076	-9.464	23.344	28.076	13.249	-32.492
3-Feb-99	178	-184.848	-12.411	24.113	-2.837	0.000	31.206	3.901	-55.319
10-Feb-99	185	-175.000	-89.474	-94.737	-505.263	-521.053	-84.211	-168.421	-126.316
17-Feb-99	192	0.000	-409.524	-195.238	-528.571	-1266.667	-276.190	-666.667	-480.952
24-Feb-99	199	-18.750	-863.158	-1284.211	-678.947	-1789.474	-1084.211	-1205.263	-768.421
	Range	-277/91%	-863/85%	-1284/91%	-679/77%	-1789/69%	-1084/83%	-1205/84%	-768/91%
	AveRemoval	-44.573	-107.652	-103.947	-117.920	-231.917	-74.414	-124.557	-98.601

Appendix H
1,1,1-Trichloroethane Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination
Results in ug/L

			Groundwater Amended with Nutrient/Yeast and Electron Donor								
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1										
9-Sep-98	31	160.77	N/D	135.46	N/D	N/D	N/D	N/D	N/D	N/D	N/D
30-Sep-98	52	16.67	58.49	19.45	N/D	N/D	31.11	24.79	N/D	15.52	23.66
20-Oct-98	72	12.36	15.30	10.51	N/D	N/D	N/D	N/D	N/D	N/D	2.46
10-Nov-98	93	11.22	4.40	12.05	N/D	N/D	N/D	N/D	1.70	N/D	1.66
2-Dec-98	115	4.40	6.90	3.72	N/D	N/D	N/D	1.70	N/D	N/D	N/D
23-Dec-98	136	5.47	4.38	2.40	N/D	N/D	N/D	N/D	N/D	N/D	N/D
30-Dec-98	143	3.11	3.71	2.57	N/D	N/D	N/D	N/D	N/D	N/D	N/D
6-Jan-99	150	5.15	6.91	7.88	N/D	2.41	4.04	N/D	N/D	N/D	N/D
14-Jan-99	158	3.55	4.56	1.49	N/D	N/D	N/D	N/D	N/D	N/D	N/D
21-Jan-99	165	3.67	4.64	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
27-Jan-99	171	2.26	3.41	1.80	N/D	N/D	N/D	N/D	N/D	N/D	1.57
3-Feb-99	178	2.04	2.32	1.21	N/D	N/D	N/D	N/D	N/D	N/D	N/D
10-Feb-99	185	1.82	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
17-Feb-99	192	2.26	4.44	1.11	N/D	N/D	N/D	N/D	N/D	N/D	N/D
24-Feb-99	199	1.40	N/D	1.22	N/D	N/D	N/D	N/D	N/D	N/D	N/D

Appendix H
1,1,1-Trichloroethane Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination
Percentage Apparent Removal — Groundwater Amended with Nutrient/Yeast and Electron Donor

Date	Experiment Day	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1								
9-Sep-98	31	15.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30-Sep-98	52	-16.68	100.00	100.00	46.81	57.62	100.00	73.47	59.55
20-Oct-98	72	14.97	100.00	100.00	100.00	100.00	100.00	100.00	83.92
10-Nov-98	93	-7.40	100.00	100.00	100.00	100.00	61.36	100.00	62.27
2-Dec-98	115	15.45	100.00	100.00	100.00	75.36	100.00	100.00	100.00
23-Dec-98	136	56.12	100.00	100.00	100.00	100.00	100.00	100.00	100.00
30-Dec-98	143	17.36	100.00	100.00	100.00	100.00	100.00	100.00	100.00
6-Jan-99	150	-53.01	100.00	65.12	41.53	100.00	100.00	100.00	100.00
14-Jan-99	158	58.03	100.00	100.00	100.00	100.00	100.00	100.00	100.00
21-Jan-99	165	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
27-Jan-99	171	20.35	100.00	100.00	100.00	100.00	100.00	100.00	53.96
3-Feb-99	178	40.69	100.00	100.00	100.00	100.00	100.00	100.00	100.00
10-Feb-99	185	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17-Feb-99	192	50.88	100.00	100.00	100.00	100.00	100.00	100.00	100.00
24-Feb-99	199	12.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Range	-53/100%	0/100%	0/100%	0/100%	0/100%	0/100%	0/100%	0/100%
Apparent Ave Removal		28.36	80.00	77.67	72.56	75.53	77.42	78.23	70.65

Appendix H
1,4-Dichlorobenzene Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination
Results in ug/L

					Groundwater Amended with Nutrient/Yeast and Electron Donor						
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1										
9-Sep-98	31	220.49	215.90	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
30-Sep-98	52	12.41	N/D	27.88	23.94	27.09	24.00	24.48	21.81	26.80	36.29
20-Oct-98	72	6.01	8.69	12.91	11.26	21.15	12.35	14.44	12.90	16.94	16.02
10-Nov-98	93	2.44	5.99	6.06	8.02	8.97	8.82	8.78	6.36	6.41	5.27
2-Dec-98	115	5.99	6.06	3.01	3.95	3.61	5.33	6.36	4.20	3.39	2.86
23-Dec-98	136	5.15	5.40	1.73	3.08	2.66	3.36	3.59	3.36	2.55	2.52
30-Dec-98	143	2.95	4.34	1.77	2.45	2.38	2.84	2.88	2.77	2.08	1.94
6-Jan-99	150	3.59	4.89	1.71	4.90	2.31	2.40	2.39	2.90	1.96	1.94
14-Jan-99	158	3.08	4.53	1.50	1.93	2.02	2.18	2.38	3.02	2.10	1.94
21-Jan-99	165	3.94	4.58	1.42	1.89	2.07	1.93	2.09	2.20	1.79	1.65
27-Jan-99	171	3.96	4.43	4.14	2.11	1.82	2.01	2.19	1.79	1.76	1.45
3-Feb-99	178	2.20	3.14	1.31	1.77	1.63	1.60	1.80	2.01	1.71	1.39
10-Feb-99	185	1.54	2.40	2.34	2.36	2.11	1.78	2.26	2.19	1.92	1.61
17-Feb-99	192	1.54	1.93	1.33	1.78	1.64	1.56	1.70	1.96	1.48	1.50
24-Feb-99	199	1.73	2.35	N/D	1.60	1.39	1.30	1.66	1.40	1.93	1.55

Appendix H
1,4-Dichlorobenzene Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination
Percentage Apparent Removal — Groundwater Amended with Nutrient/Yeast and Electron Donor

Date	Experiment Day	Unamended Groundwater Effluent (Col 1)	Nutrient/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1								
9-Sep-98	31	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
30-Sep-98	52	-124.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20-Oct-98	72	-114.81	-29.57	-143.38	-42.12	-66.17	-48.45	-94.94	-84.35
10-Nov-98	93	-148.36	-33.89	-49.75	-47.25	-46.58	-6.18	-7.01	12.02
2-Dec-98	115	49.75	34.82	40.43	12.05	-4.95	30.69	44.06	52.81
23-Dec-98	136	66.41	42.96	50.74	37.78	33.52	37.78	52.78	53.33
30-Dec-98	143	40.00	43.55	45.16	34.56	33.64	36.18	52.07	55.30
6-Jan-99	150	52.37	-0.20	52.76	50.92	51.12	40.70	59.92	60.33
14-Jan-99	158	51.30	57.40	55.41	51.88	47.46	33.33	53.64	57.17
21-Jan-99	165	63.96	58.73	54.80	57.86	54.37	51.97	60.92	63.97
27-Jan-99	171	-4.55	52.37	58.92	54.63	50.56	59.59	60.27	67.27
3-Feb-99	178	40.45	43.63	48.09	49.04	42.68	35.99	45.54	55.73
10-Feb-99	185	-51.95	1.67	12.08	25.83	5.83	8.75	20.00	32.92
17-Feb-99	192	13.64	7.77	15.03	19.17	11.92	-1.55	23.32	22.28
24-Feb-99	199	0.00	31.91	40.85	44.68	29.36	40.43	17.87	34.04
	Range	-148/100%	-34/100%	-143/100%	-47/100%	-66/100%	-48/100%	-94/100%	-84/100%
Apparent Ave Removal		2.24	27.41	25.41	29.94	22.85	27.95	32.56	38.85

Appendix H
Chlorobenzene Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Results in ug/L

					Groundwater Amended with Nutrient/Yeast and Electron Donor						
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1										
9-Sep-98	31	107.96	101.35	42.17	47.24	38.67	38.64	48.33	35.95	36.73	36.57
30-Sep-98	52	N/D	15.76	12.66	14.13	13.18	13.93	13.58	16.35	12.05	14.00
20-Oct-98	72	12.42	25.37	1.97	6.76	8.87	9.81	7.89	9.58	8.87	7.57
10-Nov-98	93	12.39	7.85	6.62	9.33	12.47	10.68	10.53	10.84	12.54	12.76
2-Dec-98	115	7.85	15.11	4.60	9.02	8.37	8.55	10.84	7.50	9.70	7.40
23-Dec-98	136	16.43	18.08	5.52	10.84	9.16	8.68	9.36	8.44	9.00	9.02
30-Dec-98	143	13.14	15.38	8.96	9.82	9.44	7.77	9.59	9.61	8.36	8.35
6-Jan-99	150	12.64	16.09	6.67	8.09	8.00	6.60	8.02	8.29	7.25	7.81
14-Jan-99	158	10.29	16.03	5.03	6.71	7.25	6.28	7.37	8.10	7.13	9.05
21-Jan-99	165	13.90	16.53	5.42	7.00	7.45	6.06	6.90	7.09	7.30	8.03
27-Jan-99	171	10.95	15.43	7.52	9.00	9.06	8.61	9.09	7.30	8.69	7.98
3-Feb-99	178	2.26	10.54	6.58	9.16	8.78	8.42	8.85	9.07	8.91	8.70
10-Feb-99	185	1.49	5.48	4.05	7.26	7.45	9.06	7.12	7.40	7.83	6.83
17-Feb-99	192	3.51	4.50	1.94	5.31	4.62	4.25	4.18	4.95	3.92	3.87
24-Feb-99	199	3.03	7.30	2.27	5.16	4.68	4.74	5.58	4.67	5.91	4.52

Appendix H
Chlorobenzene Results

USU/Hill AFB EM OU-1 Treatability Study Using Electron Donors to Enhance Dechlorination

Percentage Removal — Groundwater Amended with Nutrient/Yeast and Electron Donor

Date	Experiment Day	Unamended Groundwater Effluent (Col 1)	Nutrient/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
10-Aug-98	1								
9-Sep-98	31	60.94	53.39	61.85	61.87	52.31	64.53	63.76	63.92
30-Sep-98	52	0.00	10.34	16.37	11.61	13.83	-3.74	23.54	11.17
20-Oct-98	72	84.14	73.35	65.04	61.33	68.90	62.24	65.04	70.16
10-Nov-98	93	46.57	-18.85	-58.85	-36.05	-34.14	-38.09	-59.75	-62.55
2-Dec-98	115	41.40	40.30	44.61	43.41	28.26	50.36	35.80	51.03
23-Dec-98	136	66.40	40.04	49.34	51.99	48.23	53.32	50.22	50.11
30-Dec-98	143	31.81	36.15	38.62	49.48	37.65	37.52	45.64	45.71
6-Jan-99	150	47.23	49.72	50.28	58.98	50.16	48.48	54.94	51.46
14-Jan-99	158	51.12	58.14	54.77	60.82	54.02	49.47	55.52	43.54
21-Jan-99	165	61.01	57.65	54.93	63.34	58.26	57.11	55.84	51.42
27-Jan-99	171	31.32	41.67	41.28	44.20	41.09	52.69	43.68	48.28
3-Feb-99	178	-191.15	13.09	16.70	20.11	16.03	13.95	15.46	17.46
10-Feb-99	185	-171.81	-32.48	-35.95	-65.33	-29.93	-35.04	-42.88	-24.64
17-Feb-99	192	44.73	-18.00	-2.67	5.56	7.11	-10.00	12.89	14.00
24-Feb-99	199	25.08	29.32	35.89	35.07	23.56	36.03	19.04	38.08
	Range	-191/84%	-32/73%	-59/65%	-65/62%	-34/69%	-38/65%	-60/65%	-63/70%
Apparent Ave Removal		15.25	28.92	28.81	31.09	29.02	29.25	29.25	31.28

Appendix I
Chloride Calculations and Results

Potential Chloride Loading from Amendment Decomposition

Amendment	Formula	M.W.	Chlorine Fraction	Qty Added to Feed Water (mg/L)	Potential Chloride Loading (mg/L)
d-Biotin	$C_{10}H_{16}N_2O_3S$	244.3	0.000	20	0.00
Folic acid	$C_{19}H_{19}N_7O_6$	441.4	0.000	20	0.00
Pyridoxine hydrochloride (B_6)	$C_8H_{11}NO_3.HCl$	205.6	0.058	100	5.84
Thiamin hydrochloride(B_1)	$C_{12}H_{17}ClN_4OS.HCl$	337.3	0.036	50	1.78
Riboflavin(B_2)	$C_{17}H_{20}N_4O_6$	376.4	0.000	50	0.00
Nicotinic acid	$C_6H_5NO_2$	123.1	0.000	50	0.00
DL-calcium pantothenate	$C_9H_{16}NO_5.1/2Ca$	238.3	0.000	50	0.00
Vitamin B_{12} (cyanocobalamin)	$C_{63}H_{88}CoN_{14}O_{14}P$	1355.4	0.000	10	0.00
p-Aminobenzoic acid	$C_7H_7NO_2$	137.1	0.000	50	0.00
Lipoic acid	$C_8H_{16}O_2S_5$	208.3	0.000	50	0.00
Resazurin	$C_{12}H_6NO_4Na$	251.2	0.000	1	0.00
Yeast				20	0.00
Sodium Bicarbonate	$NaHCO_3$	84.01	0.000	1000	0.00
	Total Potential Chloride From Amendments =				7.62

Appendix I
Chloride Calculations and Results

Chloride
Results in mg/L

						Groundwater Amended with Nutrient/Yeast and Electron Donor					
Date	Experiment Day	Unamended Groundwater Influent	Vitamin/Yeast Amended Groundwater Influent	Unamended Groundwater Effluent (Col 1)	Vitamin/Yeast Amended Groundwater Effluent (Col 2)	n-Butyric Acid (Col 3)	Benzoic Acid (Col 4)	Lactic Acid (Col 5)	Propionic Acid (Col 6)	n-Propanol (Col 7)	Toluene (Col 8)
21-Jan-99	165	47.50	63.27	41.85	74.14	74.19	67.08	69.85	71.32	70.72	64.74
			mg/L Produced	-5.65	10.87	10.92	3.81	6.58	8.05	7.45	1.47